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THE EFFECT OF THE EARTH'S ROTATION ON THE VELOCITY OF LIGHT

PART I

By A. A. MICHELSON

ABSTRACT

Theory of the effect of the rotation of the earth on the velocity of light as derived on the hypothesis of a fixed ether.

Historical Remarks.—The theory was given originally in 1904. The experiment was undertaken at the urgent instance of Dr. L. Silberstein. A preliminary experiment at Mount Wilson in 1923 showed that it was necessary to resort to an exhausted pipe-line.

In the *Philosophical Magazine*, (6) **8**, 716, 1904, a plan was proposed for testing the effect of the earth's rotation on the velocity of light. The expression for the difference in path between two interfering pencils, one of which travels in a clockwise, and the other in a counterclockwise direction, may be deduced on the hypothesis of a fixed ether as follows:

If l_1 is the length of path at latitude ϕ_1 and l_2 that at latitude ϕ_2, v_1 and v_2 the corresponding linear velocities of the earth's rotation, and V the velocity of light, the difference in time required for the two pencils to return to the starting-point will be

$$T=\frac{2\,l_2v_2}{V^2-v_2^2}-\frac{2\,l_1v_1}{V^2-v_1^2}$$

or with sufficient approximation

$$T=2\left(\frac{l_2v_2-l_1v_1}{V^2}\right)$$

or if

$$l_1=l_0\cos\phi_1 \qquad \text{and} \qquad v_1=v_0\cos\phi_1$$
$$l_2=l_0\cos\phi_2 \qquad\qquad v_2=v_0\cos\phi_2$$

and

$$\phi_1-\phi_2=\frac{h}{R}$$

(R=earth's radius),

the resulting difference in phase of the two pencils will be

$$\Delta=\frac{4}{V\lambda}lh\,\omega\sin\phi,^1$$

in which ω is the earth's angular velocity, and λ the effective wavelength of the light employed.

The experiment remained in abeyance for many years, until, at the urgent instance of Dr. L. Silberstein, the writer was convinced of the importance of the work, notwithstanding serious difficulties which were anticipated in the way of raising the necessary funds. The greatest expense would be in arranging a pipe line a mile long and a foot in diameter, such as would be required for the work. In the hope that this device might not be necessary, however, it was decided to attempt the experiment in the open air at Mount Wilson.

The work was undertaken at Mount Wilson during the summer of 1923, with a circuit over one mile in length. The interference fringes between the two pencils, one of which traversed the circuit clockwise, and the other counterclockwise, were observed most clearly during the half-hour before and after sunset. But even under the best conditions, the interference fringes were so unsteady that it was found impossible to make any reliable measurements.

A doubt had been raised concerning the possibility of referring

[1] In the original article, Δ was erroneously given as half of this value. Dr. L. Silberstein (*Journal of the Optical Society*, **5**, 291, 1921) deduced the expression equivalent to the above, which was confirmed by Dr. A. C. Lunn, *ibid.*, **6**, 112, 1922, except that the area inclosed is substituted for the product lh.

any expected displacement to a fiducial zero with which to compare the results. Such a fiducial zero was furnished by providing a double circuit, in one of which the area, on which the expected displacement depends, was much greater than in the other. The impossibility of obtaining accurate results in the open-air experiments on Mount Wilson showed that it was clearly necessary to resort to a pipe line about one mile long and one foot in diameter which could be exhausted of air.

Funds for this experiment, amounting to about $17,000, were furnished by the University of Chicago, with an additional contribution of $491.55 made through the efforts of Dr. L. Silberstein. With this support it was decided to perform the experiments at Clearing, Illinois; and in this work, which is to be discussed in the next article, Dr. Gale was invited to join.

THE EFFECT OF THE EARTH'S ROTATION ON THE VELOCITY OF LIGHT

PART II

By A. A. MICHELSON AND HENRY G. GALE
Assisted by FRED PEARSON

ABSTRACT

Experimental Test of Theory.—Air was exhausted from a twelve-inch pipe line laid on the surface of the ground in the form of a rectangle 2010×1113 feet. Light from a carbon arc was divided at one corner by a thinly coated mirror into direct and reflected beams, which were reflected around the rectangle by mirrors at the corners. The two beams returning to the original mirror produced interference fringes. The beam traversing the rectangle in a counter-clockwise direction was retarded. The observed displacement of the fringes was found to be $0.230 \pm .005$, agreeing with the computed value $0.236 \pm .002$ within the limits of experimental error.

A rectangular tract of land at Clearing, Illinois, 2010 feet from east to west and 1113 feet from north to south, was carefully surveyed and staked by Dr. Kannenstine, and twelve-inch water pipes were laid straight and level around the entire circuit with a double line across one end.

The general plan of the arrangement is shown in Figure 1. Cast-iron boxes at the corners contained the mirrors. Figure 2 shows the details of one of the corner boxes. Delicate screw-and-lever systems, operated from outside the boxes through carefully fitted beveled joints, rendered it possible to adjust the mirrors readily about horizontal or vertical axes. The boxes were set in heavy concrete piers, and connected to the pipes by flexible joints of canvas and rubber. Similar joints were inserted in the pipe lines, about four hundred feet apart, and served as expansion joints.

The plane-parallel plates at A and B were lightly coated with gold, and that at C with silver, to reflect and transmit the desired proportions of light. The mirrors at D, E, and F were heavily silvered. A telephone system, consisting of portable sets kindly loaned by the Chicago Telephone Company, made it possible for an observer at A to direct assistants, one at each corner, when an adjustment of the mirrors was necessary. A Worthington air-pump, driven by a

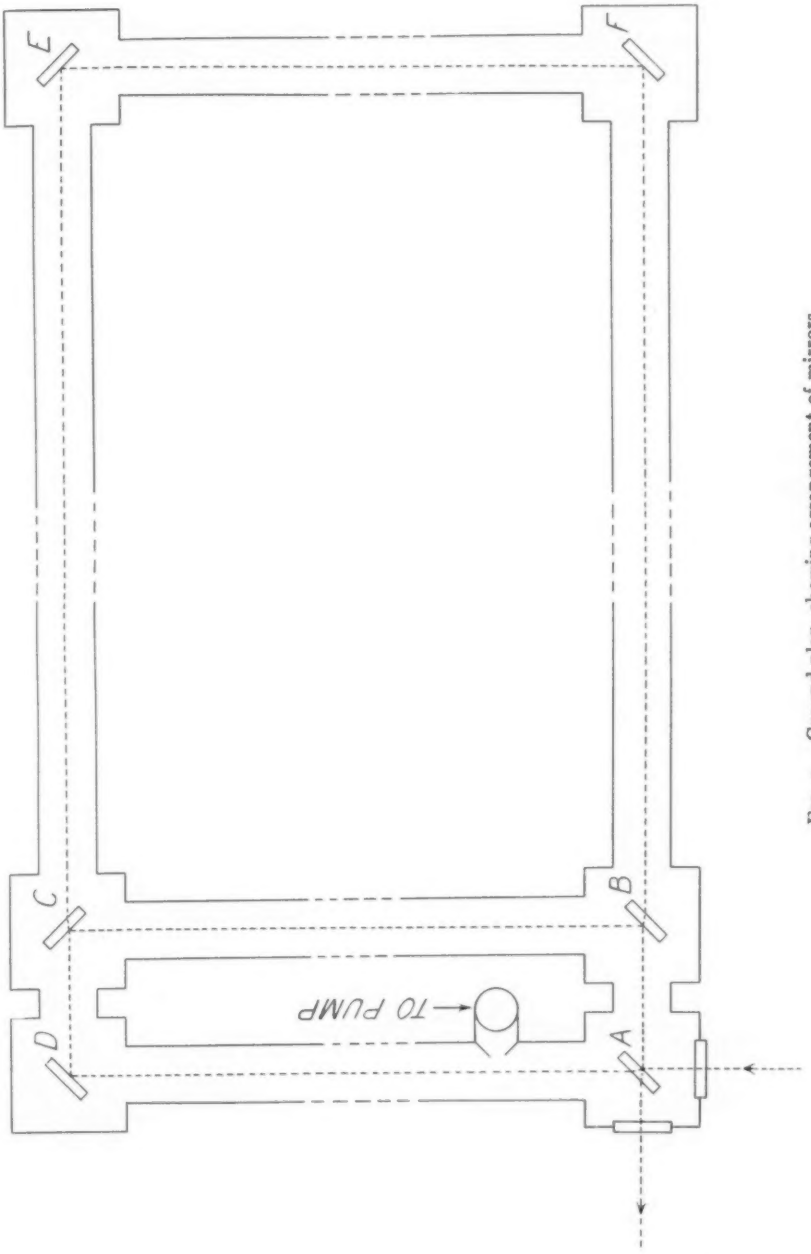

FIG. 1.—Ground plan, showing arrangement of mirrors

50 horse-power motor, reduced the pressure in the pipe to about a half-inch in three hours. Most of the measurements were made when the residual air in the pipes had been reduced to a pressure of about half an inch to one inch of mercury. At these pressures the fringes were perfectly steady, and as sharply defined as could be desired.

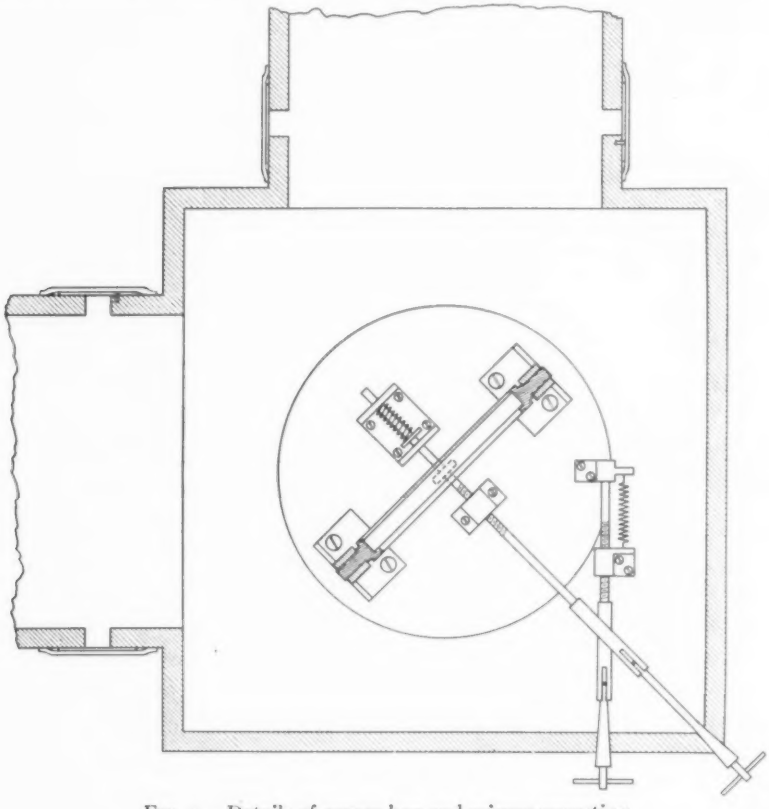

FIG. 2.—Details of corner box and mirror mounting

The fringes to be measured were those formed by the beams going in opposite directions about the circuit *ADEF*. As a fiducial mark from which to measure the displacement, a second set of fringes was formed by the mirror system *ABCD*. The area inclosed by this circuit was much too small to give a measurable displacement of the fringes, and the shifts actually recorded were those between the central fringes of the two sets.

In general the two sets of fringes will not coincide in position, entirely aside from any question of ether drift or the earth's rotation, unless the two direct images and the two reflected images of the source are exactly superposed. The central fringes of the set formed by the mirrors of the short circuit will be halfway between the direct and reflected images of the source, and the central fringe of the long line would be halfway between the direct and reflected images if there were no difference due to the earth's rotation.

To correct for any lack of superposition of the two sets of rays, the observing telescope (a six-inch achromatic objective, and two-inch micrometer eyepiece) was focused on the images of the source (arc or slit) and the apparent displacement of the central fringe of the long circuit, compared with the central fringe of the short circuit, was corrected by an amount equal to the difference in the mean positions of the two images for the two light circuits. The fringes are most conveniently observed in the overlapping cones of light an inch or so inside or outside of the focal plane.

About half of the determinations were made with the arc placed directly in front of the window at A, and about half with a condensing lens, slit, and collimating lens. The second arrangement gave much more light than the first, but there was no apparent difference in the measured displacements.

The calculated value of the displacement on the assumption of a stationary ether as well as in accordance with relativity is

$$\Delta = \frac{4A\ \omega \sin \phi}{\lambda V}$$

where Δ is the displacement in fringes, A the area in square kilometers, ϕ the latitude ($41°46'$), V the velocity of light, ω the angular velocity of the earth, and λ the effective wave-length of the light used. Measurements were made in the laboratory, comparing the fringes produced by the same set of mirrors and the same 20-ampere alternating-current arc, with fringes produced by sodium light from a bit of glass in an oxyhydrogen flame. The light from the arc was reduced to approximately the same intensity as in the experiment at Clearing, by transmitting it through a rather narrow slit in a

rotating disk. The mean of ten determinations gave $\lambda = 5700 \pm 50$ angstroms.

The displacement of the fringes due to the earth's rotation was measured on many different days, with complete readjustments of the mirrors, with the reflected image sometimes on the right and sometimes on the left of the transmitted image, and by different observers. The deflections were averaged usually in sets of twenty, in the order in which they were taken. The resulting means are given in Table I. The entire set of two hundred and sixty-nine determina-

TABLE I

Observation*	Displacement in Fringes	Number of Observations	Deviation from Mean
1	0.252	20	0.022
2	.255	20	.025
3	.193	20	.037
4	.246	20	.016
5	.235	20	.005
6	.207	26	.023
7	.232	20	.002
8	.230	20	.000
9	.217	20	.013
10	.198	20	.032
11	.252	20	.022
12	.237	20	.007
13	0.230	23	0.000
	Mean 0.230	Total 269	Av. dev. from Mean 0.016

* Observations 1 and 2 corrected for direct image only; 1–6 inclusive, without collimator; 7–13 inclusive, with collimator.

	Obs.	Calc.
Displacement	$0.230 \pm .005$	$0.236 \pm .002$

tions and their distribution about the mean value is shown graphically in Figure 3. The final displacement, expressed as a fraction of a fringe, is

$0.230 \pm .005$ obs. $\quad 0.236 \pm .002$ calc.

In view of the difficulty of the observations, this must be taken to mean that the observed and calculated shifts agree within the limits of observational error.

The successful completion of this experiment is due in no small measure to the friendly co-operation of the officials of the City of

Chicago, Colonel A. A. Sprague, commissioner of public works; Mr. H. L. Lucas, superintendent of the Water Pipe Extension Division, and to Mr. B. W. Cullen, superintendent of the South District of the same Division; to the courtesy of the Clearing

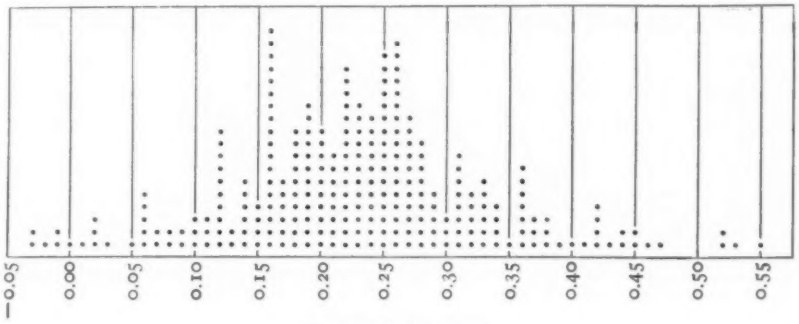

FIG. 3.—Distribution of observations

Industrial District, through Mr. Henry H. Porter; to the kindness of the Chicago Telephone Company, and to the hearty and enthusiastic support of the University. We are especially indebted to President Burton, Mr. J. C. Dinsmore, Mr. L. R. Flook, and to Messrs. Thomas O'Donnell, Joseph Purdy, and Charles Stein.

RYERSON PHYSICAL LABORATORY
UNIVERSITY OF CHICAGO
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THE PROPERTIES OF TUNGSTEN AND THE CHARACTERISTICS OF TUNGSTEN LAMPS

By W. E. FORSYTHE and A. G. WORTHING

ABSTRACT

Radiational, electrical, thermal, and mechanical properties of tungsten.—For the temperatures for which data are available these properties are shown in figures and tables, for 100° intervals, for a temperature range from 300° K. to the melting-point (3655° K.). Many interrelations between the properties are pointed out.

Characteristics of tungsten lamps.—This includes a discussion with data of changes with temperature for (1) voltage, current, wattage, candle-power, efficiency, and life of vacuum lamps; (2) dependence of current, voltage, etc., upon filament dimensions; (3) photographic effects; and (4) gas losses.

End losses.—Losses due to heat conduction from a filament to the leads and supports are discussed and methods are given to correct for them. There is given a table showing filament lengths necessary in order that the central portions of different-sized filaments, operating at various temperatures, shall be free from effects due to end losses.

Temperature, brightness, and efficiency of some commercial lamps.—Tables are given showing data for commercial lamps.

INTRODUCTION

Probably no other substance has ever been so widely studied as tungsten, either in the number of properties considered or in the range of temperature covered. Considerable data have been accumulated, parts of which have been published from time to time. Results on some of the properties of tungsten have been given by Langmuir,[1] but due to the vast amount of work which has since been done and to the different temperature scales that have been used in its presentation, this work no longer satisfies the present needs. In this paper, data obtained in the Nela Research Laboratory, together with the results of others, are set forth in a compact, consistent form on a temperature scale determined by the fundamental constants proposed for the forthcoming International Critical Tables.

This paper is divided into two parts. One deals with the properties of tungsten, the other with the characteristics of tungsten lamps. In general, properties and characteristics are given as functions of the true temperature for well-aged filaments. The accuracy of the data is indicated by the number of significant figures given. In general, the last one given is the first uncertain figure. In some cases,

[1] *Physical Review*, 7, 302, 1916.

as will be apparent, these have been rounded off to 0 or 5. Where extrapolations have been made, it has been indicated. The subdivisions are as follows:

Properties of tungsten: temperature scale (brightness temperature); spectral emissivity; average luminous emissivity; color emissivity; total emissivity; color temperature; radiation temperature; melting-point; resistivity; brightness; radiation intensity; luminous efficiency; spectra; thermionic emission; vaporization; thermal expansion; atomic heats; thermal conductivity; thermoelectric effects; deviation from Lambert's cosine law; polarization of light emitted; mechanical properties—density, lattice spacing, simple rigidity, Young's modulus, compressibility, tensile strength and reduction of area at break, hardness.

Characteristics of tungsten lamps: temperature, voltage, candlepower relations for vacuum lamps; dependence of current, voltage, etc., upon filament dimensions; wire weight; photographic effects; life of lamps; gas losses; end losses; temperature, brightness, and efficiency of some commercial lamps.

PROPERTIES OF TUNGSTEN

Temperature scale.—The temperature scale used is one recently adopted by the General Electric Company's research laboratories. On this scale the gold point is the Day and Sosman[1] value of 1336° K., and the c_2 of Wien's equation is taken as 1.433 cm deg., the value adopted for the forthcoming International Critical Tables. On this scale the palladium point is 1829° K.[2] For convenience a black body held at this temperature has been used in the calibrations.

There are several properties of tungsten that may be used in measuring temperature once the relation between the property chosen and the temperature is known. For the most part, the brightness of the tungsten surface as measured with a disappearing filament optical pyrometer with a particular standard red-glass pyrometer filter[3] has been used. Such a brightness measurement

[1] *American Journal of Science*, **29**, 93, 1910.

[2] Hyde and Forsythe, *Astrophysical Journal*, **51**, 244, 1920.

[3] Hyde, Cady, and Forsythe, *ibid.*, **42**, 294, 1915.

does not give the true temperature directly but a temperature that is somewhat lower, called the "brightness temperature."[1] The relation between this temperature and the true temperature as derived from Wien's equation is

$$\frac{1}{T}-\frac{1}{S_\lambda}=\frac{\lambda \cdot 2.303 \log e_\lambda}{c_2}, \qquad (1)$$

where T is the true temperature, S_λ the brightness temperature, and e_λ the spectral emissivity, corresponding to the wave-length λ. Using this method the accuracy of the true temperature scale in its experimental realization depends upon the accuracy attained in determining the following three factors: (1) the brightness temperature, (2) the wave-length[2] used, and (3) the spectral emissivity.[3]

Spectral emissivity.—An attempt to determine the spectral emissivity of tungsten for various temperatures was made some years ago by Mendenhall and Forsythe.[4] A black body was made of tungsten strips mounted in the form of a narrow, hollow wedge. With this device an attempt was made to measure the true temperature by observations on the inside of the wedge, and the emissivity by the ratio of the brightness of the tungsten as measured on the outside to that of the inside of the wedge. Due to inability to obtain good tungsten ribbon, poor black-body conditions prevailed, and too high emissivities resulted. The problem was later attacked by Worthing[5] who used tungsten tubes of about 1.3 mm external diameter and 0.8 mm internal diameter, with small radial holes about 0.1–0.2 mm in diameter (see Fig. 1). With such a

[1] Hyde, "Pyrometer Symposium," *Amer. Inst. Mining Met. Eng.*, p. 288, 1920; Forsythe, *Transactions Faraday Society*, **15**, 14, 1920.

[2] Forsythe, *Journal of the Optical Society of America*, **5**, 89, 1921.

[3] *Physical Review*, **10**, 377, 1917; *Zeitschrift für Physik*, **22**, 9, 1924; *General Electric Review*, 1924. See, also, Burgess and Waltenberg, *Bulletin Bureau of Standards*, **11**, 591, 1915; Pirani, *Zeitschrift für Physik*, **13**, 753, 1912; Pirani and Meyer, *Elektrotech. u. Maschinenbau*, **33**, 397, 444, 1915; Pirani, *Verh. d. deut. physik. Gesell.*, **13**, 19, 1911; Langmuir, *Physical Review*, **6**, 138, 1915; Langmuir, *ibid.*, **7**, 302, 1916; Shackelford, *ibid.*, **8**, 470, 1916; Henning and House, *Zeitschrift für Physik*, **16**, 63, 1923; Pirani and Meyer, *Verh. d. deut. physik. Gesell.*, **14**, 681, 1912; Pirani, *Physikalische Zeitschrift*, **13**, 753, 1912; Lax and Pirani, *Zeitschrift für Physik*, **22**, 273, 1924.

[4] *Astrophysical Journal*, **37**, 38, 1915.

[5] *Physical Review*, **10**, 377, 1917.

tungsten-tube black body, the true temperature was determined from observations of the radiation coming from the small radial holes, and the emissivity from the ratio of the brightness of the tungsten measured on the outer surface of the tube to the brightness of the black body measured through the small radial holes. Calculations using measured values of the heat conductivity showed

FIG. 1.—Photograph showing tungsten tube black body with pyrometer filament projected against small radial hole.

that the difference in temperature between the inside and outside of the tungsten tube was small, amounting to not more than 3° at a temperature of 2600° K. Corrections were made for the calculated differences.

Measurements of normal emissivity for red ($\lambda = 0.665\ \mu$) and for blue ($\lambda = 0.467\ \mu$) were made over a range of temperatures from about 1000° K. to 3200° K. (Table I). These values of emissivity

have been checked by reflectivity measurements at room temperature and at 1300° K. In Figure 2 are given the results that were obtained. Variations of emissivity with wave-length for a wide range of wave-lengths, including infra-red[1,2] and ultra-violet regions,[3] are shown in Figure 3 for several temperatures.

Average luminous emissivity.—The ratio of the total normal brightness of tungsten to that of a black body at the same temperature is the average normal luminous emissivity. This may be obtained either by direct comparison of the tungsten brightness with that of a black body or by computation, making use of the crova wave-length.[4] Both methods have been used in obtaining the values given in Figure 2 and Table I.

Color emissivity.—The ratio of the normal brightness of tungsten at a temperature T to that of a black body at a temperature equal to its color temperature (see below) is called the "color emissivity."[5] The following equation gives the color emissivity e_c (Fig. 2 and Table I) as a function of T_c, the color temperature; S, the brightness temperature; and the wave-length, λ.

$$\log e_c = \frac{c_2}{2.303\lambda} \cdot \left(\frac{1}{T_c} - \frac{1}{S}\right). \qquad (2)$$

In a study of the radiation laws Hyde[6] stated his criterion I for incandescent metals. For its fulfilment, this criterion required that the ratio of the brightness of a source for two different color temperatures shall be the same as for a black body for the same two temperatures. This would mean constancy of color emissivity. Hyde showed that the ratio of brightnesses for tungsten was less than for the black body. This means that he found the color emissivity of tungsten to decrease with increase in temperature. This is in agreement with values given in Table I.

[1] Weniger and Pfund, *Physical Review*, **14**, 427, 1919.

[2] Coblentz, *Bulletin of the Bureau of Standards*, **5**, 312, 1918.

[3] Hulburt, *Astrophysical Journal*, **45**, 149, 1917.

[4] Forsythe, *Journal of Franklin Institute*, **197**, 517, 1924.

[5] Worthing, "Pyrometer Symposium," *Amer. Inst. Mining Met. Eng.*, p. 397, 1920.

[6] *Astrophysical Journal*, **36**, 89, 1913.

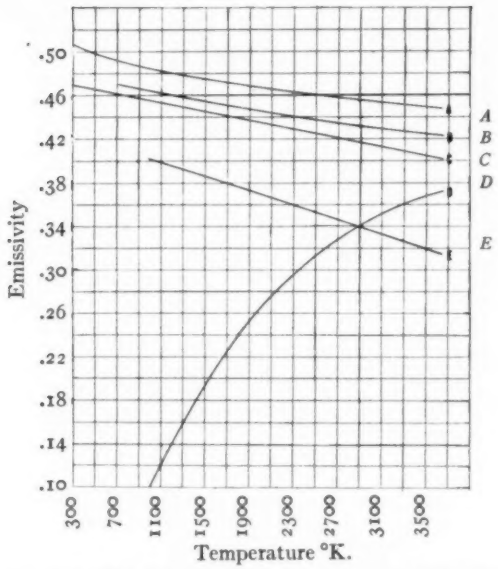


FIG. 2.—Various emissivities of tungsten as functions of temperature. Curve *A*, normal spectral emissivity for blue ($\lambda = 0.467\ \mu$). Curve *C*, normal spectral emissivity for red ($\lambda = 0.665\ \mu$). Curve *B*, average normal luminous emissivity. Curve *E*, normal color emissivity. Curve *D*, total emissivity.

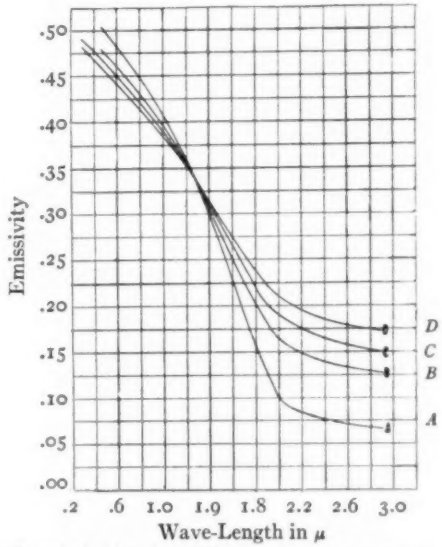


FIG. 3.—Spectral emissivities for different temperatures as a function of the wave-length over a wide range. Curve *A*, $T = 300°$ K. Curve *B*, $T = 1300°$ K. Curve *C*, $T = 1700°$ K. Curve *D*, $T = 2100°$ K.

TABLE I—A†

PROPERTIES OF TUNGSTEN

Temperature Degrees K. T	Spectral Emissivity $\epsilon_{0.665\,\mu}$	Spectral Emissivity $\epsilon_{0.467\,\mu}$	Average Luminous Emissivity ϵ_v	Color Emissivity ϵ_c	Total Emissivity ϵ_t	Brightness Temperature $S_{0.665\,\mu}$	Color Temperature T_c	Radiation Temperature T_R	Relative Lengths at Different Temperatures L/L_o	Thermal Conductivity watts/cm deg. K.	Atomic Heats cal./g atom deg. C_p	Thompson Effect Microvolts degree
300	.470	.505			.032				1.0000			
400	.468	.501			.042				1.0005			
500	.466	.498			.053				1.0010			
600	.464	.495			.064				1.0014			
700	.462	.492			.076				1.0018			
800	.460	.490			.088				1.0023			
900	.458	.488			.101				1.0028			
1000	.456	.486	.464	.396	.114	966	1006	581	1.0032	.84*	6.20	
1100	.454	.484	.463	.393	.128	1058	1108	659	1.0036	.87*	6.35	
1200	.452	.482	.462	.391	.143	1149	1210	738	1.0041	.90*	6.50	
1300	.450	.480	.460	.388	.158	1240	1312	819	1.0046	.93	6.65	
1400	.448	.478	.459	.386	.175	1330	1414	905	1.0052	.96	6.80	
1500	.445	.476	.457	.383	.192	1420	1517	991	1.0057	.99	6.95	
1600	.443	.475	.456	.381	.207	1509	1619	1080	1.0063	1.02	7.10	
1700	.441	.473	.455	.378	.222	1597	1722	1167	1.0069	1.04	7.25	
1800	.439	.472	.454	.376	.236	1684	1825	1254	1.0075	1.07	7.40	−18
1900	.437	.470	.453	.373	.249	1771	1929	1342	1.0081	1.09	7.55	−20
2000	.435	.469	.452	.370	.260	1857	2033	1428	1.0088	1.11	7.70	−22
2100	.433	.467	.450	.367	.270	1943	2137	1514	1.0094	1.13	7.85	−24
2200	.431	.466	.449	.364	.279	2026	2242	1601	1.0101	1.15	8.00	−26
2300	.429	.464	.448	.362	.288	2109	2347	1688	1.0108	1.17	8.15	−28
2400	.427	.463	.447	.359	.296	2192	2452	1775	1.0116	1.19	8.30	−30
2500	.425	.462	.446	.356	.303	2274	2557	1859	1.0124	1.21	8.45	
2600	.423	.460	.444	.353	.311	2356	2663	1945	1.0132	1.23*		
2700	.421	.459	.443	.350	.318	2437	2770	2031	1.0140	1.25*		
2800	.419	.458	.442	.347	.323	2516	2878	2116	1.0149*	1.27*		
2900	.417	.456	.441	.345	.329	2595	2986	2202	1.016*			
3000	.415	.455	.440	.343	.334	2673	3094	2286	1.017*			
3100	.413	.454	.438	.341	.337	2750	3202	2371	1.018*			
3200	.411	.452	.437	.338*	.341*	2827	3311*	2455*	1.019*			
3300	.409	.451	.436	.335*	.344*	2903	3422*	2538*	1.020*			
3400	.407*	.450*	.435*	.332*	.348*	2978	3533*	2621*	1.021*			
3500	.405*	.449*	.434*	.329*	.351*	3053	3646*	2704*	1.023*			
3655‡	.402*	.447*	.433*	.324*	.354*	3165	3817*					

* These values are extrapolated.
† Data given in this table apply to aged tungsten filaments.
‡ Melting-point.

‡ Melting-point.

TABLE I—B*

PROPERTIES OF TUNGSTEN

Temperature Degrees K. T	Resistivity Microohms cm ρ‡	$\frac{T\,d\rho}{\rho\,dT}$ § ‡	Normal Brightness Candles per cm² B_n	$\frac{T\,dB_n}{B_n\,dT}$	Crova Wave-Length λ_c‖	Total Radiation Intensity watts/cm² η	$\frac{T\,d\eta}{\eta\,dT}$	Luminous Efficiency Lumens per watt eff.	$\frac{T}{(eff.)}\frac{d(eff.)}{dT}$	Electron Emission amp./cm² i	$\frac{T\,di}{i\,dT}$	Rate of Vaporization Grams per cm²/sec v	$\frac{T\,dv}{v\,dT}$
300.....	5.64	.....	.....	.....	.....	.0015	.....	.....	.....	.....	.....	.....	.....
400.....	8.06	.....	.....	.....	.....	.006	.....	.....	.....	.....	.....	.....	.....
500.....	10.74	.....	.....	.....	.....	.019	.....	.....	.....	.....	.....	.....	.....
600.....	13.54	.....	.....	.....	.....	.048	.....	.....	.....	.....	.....	.....	.....
700.....	16.46	.....	.....	.....	.....	.105	.....	.....	.....	.....	.....	.....	.....
800.....	19.47	.....	.....	.....	.....	.206	.....	.....	.....	.....	.....	.....	.....
900.....	22.58	.....	.....	.....	.....	.379	.....	.....	.....	.....	.....	.....	.....
1000.....	25.70	1.21	.00012	22.	.6077	.654	5.35	.....	.....	.....	.....	.....	.....
1100.....	28.85	1.20	.0010	21.	.6038	1.072	5.35	.....	.....	.....	.....	.....	.....
1200.....	32.02	1.20	.006	20.	.6004	1.691	5.35	.....	.....	.....	.....	.....	.....
1300.....	35.24	1.20	.029	18.6	.5971	2.576	5.35	.....	.....	.....	.....	.....	.....
1400.....	38.52	1.20	.11	17.2	.5934	3.82	5.29	0.09	11.8	5.75×10^{-9}	39.6	.....	.....
1500.....	41.85	1.20	.33	16.1	.5902	5.55	5.23	0.20	10.8	7.58×10^{-8}	37.1	.....	.....
1600.....	45.22	1.20	.92	15.2	.5874	7.77	5.15	0.40	10.0	8.05×10^{-7}	34.9	3.7×10^{-20}	67
1700.....	48.63	1.20	2.26	14.4	.5850	10.59	5.07	0.71	9.3	6.31×10^{-6}	33.0	1.92×10^{-18}	63
1800.....	52.08	1.20	5.05	13.7	.5826	14.22	4.99	1.16	8.7	3.92×10^{-5}	31.3	6.22×10^{-17}	59
1900.....	55.57	1.20	10.40	13.0	.5806	18.55	4.91	1.88	8.1	2.04×10^{-4}	29.7	1.41×10^{-15}	56
2000.....	59.10	1.20	20.0	12.3	.5785	23.72	4.85	2.78	7.5	8.92×10^{-4}	28.3	2.32×10^{-14}	53
2100.....	62.65	1.20	35.6	11.7	.5769	29.82	4.79	3.95	6.9	3.46×10^{-3}	27.1	2.91×10^{-13}	50
2200.....	66.25	1.20	61.3	11.2	.5753	37.18	4.74	5.47	6.4	1.14×10^{-2}	25.9	2.90×10^{-12}	48
2300.....	69.90	1.20	100.5	10.8	.5737	45.9	4.69	7.25	6.0	3.63×10^{-2}	24.9	2.34×10^{-11}	46
2400.....	73.55	1.20	157.0	10.3	.5724	55.8	4.64	9.37	5.6	1.02×10^{-1}	24.0	1.58×10^{-10}	44
2500.....	77.25	1.20	237.5	9.9	.5711	67.6	4.59	11.67	5.3	2.67×10^{-1}	23.1	9.18×10^{-10}	42
2600.....	81.0	1.20	347.0	9.6	.5701	80.8	4.55	14.28	5.0	6.48×10^{-1}	22.3	4.64×10^{-9}	40
2700.....	84.7	1.20	498.0	9.2	.5691	96.2	4.51	17.26	4.7	1.47	21.5	2.06×10^{-8}	38
2800.....	88.5	1.20	694.	8.9	.5682	112.9	4.47	20.43	4.4	3.21	20.8	8.28×10^{-8}	36
2900.....	92.3	1.20	949.	8.6	.5674	132.1	4.43	23.80	4.1	.....	.....	2.99×10^{-7}	35
3000.....	96.2	1.20	1257.	8.3	.5666	153.9	4.40	27.10	3.8	.....	.....	9.92×10^{-7}	34
3100.....	100.0	1.20	1647.	8.0	.5659	177.5	4.37	31.0	3.6	.....	.....	3.01×10^{-6}	33
3200.....	103.8	1.20	2110.	7.8	.5652	203.	4.34	34.6	3.4	.....	.....	8.79×10^{-6}	32
3300.....	107.8	1.20	2685.	7.7	.5645	232.	4.31	38.5	3.3	.....	.....	2.29×10^{-5}	31
3400.....	111.7	1.20	3370.	7.6	.5638	264.†	4.29†	42.6†	3.2†	.....	.....	5.74×10^{-5}	30
3500.....	115.7	1.20	4220.	7.4	.5631	300.†	4.27†	45.9†	3.1†	.....	.....	1.36×10^{-4}	30
3655¶.....	121.8†	1.20†	5740.	7.3	.5621	360.†	.....	53.1†	3.0†	.....	.....	4.70×10^{-4}	28

* Data given in this table apply to well-aged tungsten.

† These values are extrapolated.

‡ These values depend on the dimensions at room temperature. In intercomparing values for the various properties, account should be taken of the thermal expansion as well as the variation from Lambert's cosine law.

§ The constancy of this quantity at high temperatures for a particular specimen makes temperature determinations from resistance measurements simple, since the temperature corresponding to any resistance can then be computed from resistances at two known temperatures.

‖ The values of the Crova wave-lengths given are the limiting values. The Crova wave-length between two temperatures is the average of the two corresponding limiting Crova wave-lengths.

¶ Melting-point.

TABLE I—C

SOME ELECTRICAL AND RADIATIONAL CHARACTERISTICS OF A TUNGSTEN WIRE 1 CM LONG AND 1 CM IN DIAMETER MOUNTED IN A VACUUM

The function $V'^{\frac{3}{2}}I'$ is independent of the filament diameter. For the dependence of current, voltage, etc., upon filament dimensions see equations 18–25. See also Table VI.

Temperature Degrees K. T	Resistance Ohms R'	Potential Drop Volts V'	Current Amperes I'	Power Watts W'	$V'^{\frac{3}{2}}I'$	Mean Horizontal Candle-Power C'*†	Luminous Flux Lumens*
300....	7.18×10^{-6}	$.057\times10^{-3}$	$.008\times10^{+3}$	.00045	$.11\times10^{-3}$	.....	.....
400....	10.26	.38	.037	.014	1.3	.....	.....
500....	13.66	.85	.062	.053	3.4	.....	.....
600....	17.23	1.57	.091	.143	7.1	.....	.....
700....	20.96	2.60	.124	.323	13.0	.....	.....
800....	24.80	4.00	.161	.644	21.8	.....	.....
900....	28.75	5.87	.204	1.200	34.6	.....	.....
1000....	32.73	8.23	.251	2.068	51.9	.00012	.012
1100....	36.84	11.19	.304	3.392	75.2	.0010	.010
1200....	40.80	14.77	.362	5.35	105.3	.006	.06
1300....	44.90	19.15	.427	8.17	144.2	.029	.29
1400....	49.10	24.5	.494	12.12	194.0	.11	1.1
1500....	53.35	30.7	.575	17.62	255.	.33	3.3
1600....	57.60	37.7	.655	24.72	328.	.95	9.5
1700....	61.95	45.7	.738	33.72	413.	2.34	23.5
1800....	66.35	54.9	.827	45.35	515.	5.22	52.4
1900....	70.75	64.2	.908	58.30	622.	10.78	108.3
2000....	75.20	75.5	1.004	75.8	756.	20.75	208.5
2100....	79.80	87.2	1.093	95.4	899.	37.0	372.
2200....	84.40	100.4	1.190	119.5	1064.	63.8	641.
2300....	89.00	114.6	1.287	147.5	1247.	104.7	1052.
2400....	93.65	129.4	1.383	179.0	1442.	164.0	1648.
2500....	98.40	146.3	1.487	217.5	1670.	248.0	2490.
2600....	103.2	164.1	1.590	260.8	1915.	363.0	3650.
2700....	107.8	182.9	1.700	310.5	2180.	522.0	5240.
2800....	112.7	203.0	1.800	365.5	2470.	730.	7330.
2900....	117.5	224.2	1.910	428.0	2780.	1000.	10050.
3000....	122.5	247.7	2.020	501.0	3130.	1325.	13300.
3100....	127.4	272.	2.130	578.5	3495.	1740.	17500.
3200....	132.2	296.	2.24	663.	3875.	2235.	22450.
3300....	137.3	323.	2.35	760.	4295.	2850.	28650.
3400....	142.2	351.	2.47	866.	4740.	3580.	36000.
3500....	147.2	381.	2.59	985.	5230.	4500.	45200.
3655....	155.0	428.	2.76	1180.	5950.	6150.	61800.

* As measured through clear glass bulbs.

† Differences between these values and the brightnesses in Table I—*B* are due to Lambert's cosine-law variations, thermal expansion, and 1 per cent bulb absorption.

Total emissivity.—Total emissivity[1] is defined by the following:

$$\eta = e_t \sigma T^4 , \qquad (3)$$

where η is the rate of total energy radiation per unit area, σ the Stefan-Boltzmann constant, T the temperature, and e_t the total emissivity. Since, for a filament at high temperatures mounted *in*

[1] Worthing and Forsythe, *Physical Review*, **18**, 144, 1921.

vacuo the wattage input corrected for end losses (see below) divided by the area of the filament surface gives η, total emissivities (Fig. 2 and Table X) are thus easily obtainable once the temperature and the thermal expansion are known. Values below 1200° K. were furnished by Dr. H. A. Jones,[1] of the Research Laboratory at Schenectady.

Color temperature.—A light-source the integral color of which may be matched with that of a black body at some definite temperature is said to have a color temperature. As defined, color temperature[2] is the temperature of a black body which has the same integral color as the source studied. Color matchings[3] for such determinations of color temperature can be most satisfactorily made with a regular photometer set-up, using a contrast photometer. The color temperatures of tungsten were determined[4] by direct comparisons of tungsten lamps with a black body by this method for a temperature range of from about 1700° to 2600° K. If the black body and the source studied, as with tungsten, have the same spectral-energy distribution when color matched, such color temperatures can be obtained by comparisons of the relative spectral brightnesses for two wave-lengths. The best color match with tungsten and a black body as determined by spectral brightness ratios at 0.467 μ and 0.665 μ shows a deviation[5] at 0.567 μ varying from about 0.8 per cent at 1600° K. to about 1.6 per cent at 2600° K., the tungsten being the brighter. The color temperatures of tungsten as a function of the brightness temperature for $\lambda = 0.665\ \mu$ have thus been determined by measuring the ratio of the red ($\lambda = 0.665\ \mu$) to the blue brightness ($\lambda = 0.467\ \mu$), called the "red-blue ratio," for temperatures between 1200° and 3000° K.[6] Using the red-and-blue emissivities, the color temperature and brightness-temperature relations were also calculated. Results obtained by

[1] To be published.

[2] Hyde, Cady, and Forsythe, *Physical Review*, **10**, 395, 1917.

[3] Forsythe, *Journal of the Optical Society of America*, **6**, 476, 1922; Hyde, Cady, and Forsythe, *Physical Review*, **10**, 396, 1917.

[4] *Ibid.*, p. 401, 1917.

[5] Hyde, *Astrophysical Journal*, **36**, 114, 1912; Forsythe, *Journal of the Optical Society of America*, **7**, 1115, 1923.

[6] Forsythe, *ibid.*, p. 1118, 1923.

these two methods differed slightly. A weighted average of the two sets has been adopted as the best approximation (Table I and Fig. 4). Such values are in good agreement with values found by the direct photometric comparison except at very low and very high temperatures.

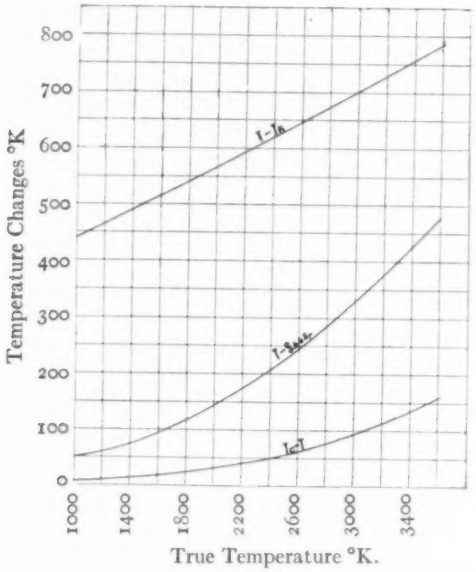


FIG. 4.—Curves showing the difference between true temperature (T) and color temperature (T_c), curve (T_c-T); and brightness temperature (S), curve ($T-S$ 0.665μ); and radiation temperature (T_R), curve ($T-T_R$).

Radiation temperature.—If the temperature of a tungsten filament is determined from the rate of total energy radiation as though it were a black body, a value, lower than the true temperature, called the "radiation temperature"[1] (T_R) is obtained. Thus, as in equation (3),

$$\eta=\sigma T_R^4 . \tag{4}$$

From equations 3 and 4 it follows that the true temperature and the radiation temperature are related as follows (Fig. 2 and Table I):

$$T_R=\sqrt[4]{e_t}\cdot T . \tag{5}$$

[1] Hyde, "Pyrometer Symposium," *Amer. Inst. Mining Met. Eng.*, p. 288, 1920.

Melting-point.—Many experimenters have sought the melting-point of tungsten. Excluding cases where there were very questionable, extended extrapolations, the methods used have depended upon the disappearing filament pyrometer for the measurement of spectral-brightness temperature either of tungsten or of a black body made of tungsten at the melting-point. In the former case, the spectral emissivity of tungsten at the melting-point must be employed as in equation 1 to obtain the true temperature; in the latter case, the result obtained is the true temperature.

In order to melt the tungsten it was electrically heated either in wire or rod form, or as arc terminals. When the true temperature has been measured directly, filaments or terminals with small radially drilled holes have been used.

The results of the various workers have been summed up by one of the authors.[1] Taking into consideration only the results for which the metallurgy of tungsten and the art of pyrometry have been on a satisfactorily sound basis, 3655° K. was obtained as the best weighted average for the melting-point of tungsten. This, with the possible exception of carbon, is probably the highest of all melting-points.

Resistivity.—The resistivity of tungsten[2] was obtained from the same readings as was the total emissivity. It was found that the resistance and temperature are related by the following equation:

$$\frac{R}{R_0}=\left(\frac{T}{T_0}\right)^{\beta}, \tag{6}$$

where β is a constant having a value of about 1.20. While β varies slightly from sample to sample, the relation between log R and log T was always found to be linear—to within the errors of measurements—for the range 1000°–3200° K. There is but a small departure from the linear relation even down to room temperature (Table I). Values below 1000° K. were furnished by Dr. Jones, of Schenectady.

[1] Worthing, *ibid.*, p. 374, 1920; *Zeitschrift für Physik*, **22**, 9, 1924; *General Electric Review*, 1924.

[2] Worthing, *Physical Review*, **12**, 207, 1918; *ibid.*, **18**, 144, 1921.

Variation of resistivity with pressure, P,[1] for the range $O<P<$ 12,000 kg wt./cm² is given by

$$\frac{1}{\rho}\frac{d\rho}{dp}=-1.35\times10^{-6}\frac{1}{\text{kg wt./cm}^2}. \qquad (7)$$

The variation of this function with temperature between 0° C. and 100° C. amounts to only 2 or 3 per cent.

Brightness.—Normal brightness of a material is defined as the candle-power per square centimeter of a flat piece of material measured normal to the surface. In this paper the brightnesses given are independent of the characteristics of a particular observer's eye, being based on the Middlekauff and Skogland[2] candle-power scale. Three methods have been used. The first method consisted[3] in making candle-power determinations of a known length of uniformly heated filaments with known cross-sections. The second method consisted in measuring the brightness of the surface with an optical pyrometer calibrated as a brightness photometer.[4] The third method consisted in calculating the brightness from the color emissivity and the brightness of a black body. The values given in Table I are the weighted averages of normal brightnesses found by the three methods mentioned above. If the average brightness in all directions is desired, these values must be increased by about 5 per cent to correct for the variation of tungsten from Lambert's cosine law (see below).

Radiation intensity.—Radiation intensity, η (Table I),[5] is the ratio of the rate of total energy output of a source to its surface. For tungsten at high temperatures the rate of total energy output may be taken as the wattage input of a filament mounted *in vacuo* when end losses are either eliminated or corrected for by one of the methods outlined below. It is to be noted that the values of η given in Table I refer to a unit area at the temperatures given.

[1] Bridgman, *Proceedings of the National Academy of Science*, **6**, 505, 1920.

[2] *Bulletin of the Bureau of Standards*, **2**, 484, 1914.

[3] Forsythe, *Physical Review*, **19**, 436, 1922.

[4] Forsythe, *Journal of the Franklin Institute*, **197**, 517, 1924.

[5] Worthing, *Physical Review*, **10**, 393, 1917.

Efficiency.—The efficiency of a tungsten lamp is the ratio of the output in lumens to the input in watts,[1] that is, in lumens per watt. The luminous efficiency of tungsten as a material (Table I) is the efficiency of the lamp corrected for various lamp losses (see below).

The efficiency of tungsten as a light-source increases with the temperature due to the shift of the point of maximum intensity toward the wave-length of maximum visibility. There is at the same time a decrease in the efficiency due to an increase in the total emissivity and a decrease in the average visible emissivity with an increase in temperature as can be seen from the curves in Figure 2. This means that the luminous efficiency of tungsten approaches that of a black body at high temperatures.

Efficiencies computed from observed B_π, η, L/L_0, and Lambert's cosine-law deviation were found to be about $1\frac{1}{2}$ per cent less than the directly measured efficiencies of ordinary 40-watt straight filament lamps after correcting for bulb absorption and end losses. This difference was ascribed to uncertainties in end-loss corrections, Lambert's cosine-law correction, deviations from actual color match with a black body, and in determination of lamp-filament temperatures. Values given in the table have been adjusted on these assumptions to eliminate differences.

A number of the electrical and radiational characteristics of a cylindrical tungsten wire of one-centimeter length and one-centimeter diameter have been found useful. In Table I, C, a number of such characteristics are given as a function of the temperature. The function $V'\sqrt[3]{I'}$ (equation 25) given in column 6 of this table is useful in estimating the temperature of a straight filament mounted in a vacuum, providing the length is known. It is also useful in maintaining at a constant temperature a filament whose diameter varies during burning, as for instance in a study of the rate of evaporation of a filament. The use of this function will give correct results only when the resistivity and surface condition do not change.

Spectra.—The ordinary arc and spark spectra of tungsten contain several thousand lines. Of these only a few important ones

[1] Hyde, Cady, and Forsythe, *ibid.*, p. 401, 1917.

have been selected for Table II. Data on wave-lengths,[1] relative intensities,[2] lines that reverse in the arc,[3] and ultimate rays[4] have been taken from different sources.

TABLE II

STRONGEST ARC AND SPARK LINES OF TUNGSTEN

λ in A	Intensity Arc	Intensity Spark		λ in A	Intensity Arc	Intensity Spark	
2397.110		10	*U*	4484.197	10		
2702.127		10		4843.829	10		
3215.578		5	*U*				
3572.477		10		5006.169	10	10	
3592.426		10		5015.334	10		
3613.793		10	*U*				
3641.419		10		5053.300	15	15	*R*
3736.220		10		5224.680	20	20	
4008.769	10	10	*U*	5492.331	15	15	
.....	.....			5514.712	20	20	
.....	.....			5648.391	10	10	
4294.623	10	10		5735.093	15		
4302.123	8	5	*U*	5804.844	10		

R. These lines may appear reversed in the arc.
U. These lines are ultimate rays.

The long-wave photo-electric limit for tungsten, i.e., the longest wave-length of radiation which can, by incidence on the surface of tungsten, cause the emission of electrons, is 2615° A.[5]

The orbital energy levels, I/N, for X-rays shown in Figure 5 are those given by Bohr and Coster,[6] corrected, however, to agree with a calcite spacing of 3.028 A as adopted for the forthcoming International Critical Tables. The wave-lengths given are the average of several determinations.[7] The quantum notation is the recent

[1] Belke, *Zeitschrift für wiss. Photographie*, **17**, 132, 1917.

[2] Exner and Hascheck, *Die Spektren der Elemente*, 1911.

[3] Hagenbach and Konen, *Atlas of Emission Spectra*.

[4] Gramont, *Comptes Rendus*, **171**, 1106, 1920.

[5] Hammer, *Physical Review*, **20**, 198, 1922.

[6] *Zeitschrift für Physik*, **12**, 342, 1923.

[7] A. H. Compton, *Physical Review*, **7**, 646, 1916; **8**, 753, 1916; Siegbahn, *Philosophical Magazine*, **38**, 639, 1919; Stenstrom, Thesis, Lund, 1919; Duane and Shimizu, *Physical Review*, **16**, 526, 1920; Duane and Patterson, *Proceedings of the National Academy of Science*, **6**, 518, 1920; Duane and Stenstorm, *ibid.*, p. 607, 1920; Hjalmar, *Zeitschrift für Physik*, **15**, 65, 1923.

one adopted by Bohr and Coster. There are certain additional lines which cannot be incorporated in this figure.

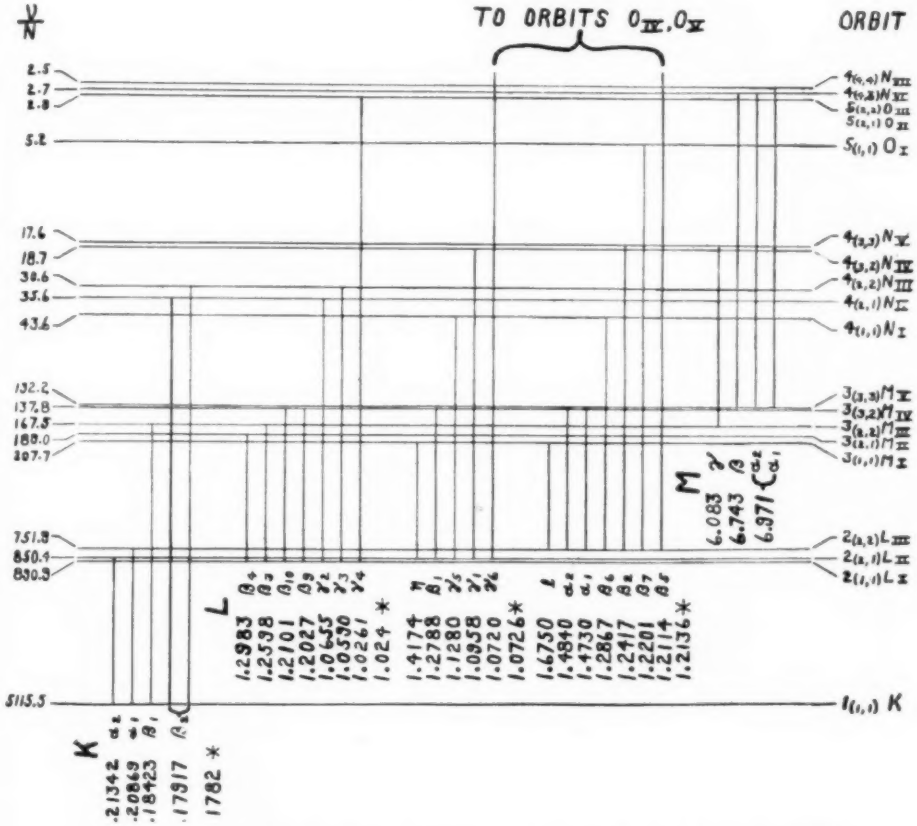


FIG. 5.—Chart showing X-ray spectra for the normal tungsten atom (calcite spacing equals 3°028 A). Orbital energy levels for the *K*, *L*, *M*, *N*, and *O* orbits are expressed in units equivalent to the energy level of the innermost orbit of the hydrogen atom when corrected for the finite mass of its electron. The scale is logarithmic. Both energy levels and quantum designations are taken from a paper by Bohr and Coster (see p. 15, n. 6). The wave-lengths are averages taken from several papers (see p. 15, n. 7). Values starred are experimental absorption limits.

Thermionic emission.—The values of electron emission given in Table I have been furnished by Dr. Dushman,[1] of the General

[1] *General Electric Review*, **26**, 154, 1923; Davisson and Germer, *Physical Review*, **20**, 300, 1922.

Electric Research Laboratory at Schenectady. His results are given in equation form by

$$i = AT^2 e^{-\frac{b_0}{T}}, \tag{8}$$

where i is the thermionic current density, T the temperature, e the natural logarithm base, A the constant 60.2 amp./cm², and b_0 a specific constant for the material having the value 52,600°.

Vaporization.—The rates of vaporization of tungsten given in Table I are taken from data by Dr. Langmuir,[1] corrected for temperature by Dr. H. A. Jones, of the General Electric Research Laboratory at Schenectady.

Thermal expansion.—Expansion[2] of tungsten between 300° and 900° K. was determined in the usual manner. For higher temperatures, use was made of hairpin tungsten filaments mounted in special lamp bulbs, permitting expansion measurements on 18 cm of the filament which was uniformly heated. Results (Table I) are well represented by

$$\frac{L - L_0}{L_0} = 4.44 \times 10^{-6}(T-300) + 4.5 \times 10^{-11}(T-300)^2 + 2.20 \times 10^{-13}(T-300)^3, \tag{9}$$

where L_0 and L refer respectively to filament lengths at 300° K. and at the temperature T. The coefficient of expansion at 300°, 1300°, and 2300° K. are, respectively, 4.44×10^{-6}, 5.19×10^{-6}, and 7.26×10^{-6} per degree.

Atomic heats.—The performance of a filament *in vacuo*, while passing from one steady state to another in consequence of a change in the heating current, depends in part upon the atomic heat.[3] With a set-up by which the current through a tungsten filament could be measured at different time-intervals after the applied voltage had changed, data were obtained which yielded atomic heat (Table I).

[1] *Physical Review, ibid.*, **2**, 329, 1913.

[2] Worthing, *ibid.*, **10**, 638, 1917.

[3] Worthing, *ibid.*, **12**, 199, 1918. See also, Corbino, *Zeitschrift für Physik*, **13**, 375, 1912; Pirani, *Verh. d. deut. physik. Gesell.*, **14**, 1037, 1912; Gaehr, *Physical Review*, **12**, 396, 1918; Smith and Bigler, *ibid.*, **19**, 268, 1922.

Thermal conductivity.—Variation of the temperature of a filament near a lead-in wire is caused by conduction of heat from the filament to the lead. From observed temperature variations and other known properties of tungsten, heat-conductivity[1] determinations of tungsten were made (Table I) for the range 1500° to 2500° K. For this range the relation between temperature and heat conductivity is linear.

Thermo-electric effect.—Variation of temperature near a lead-in wire depends upon the direction of the heating current. This variation is due to the Thompson effect.[2] By studying this variation with change in current direction, determinations of the Thompson e.m.f. (Table I) were made for the range 1500° to 2200° K.

Thermo-electric properties of tungsten for temperatures between 0° and 100° C. and pressures between atmospheric and 12,000 kg wt./cm² have been determined by Bridgman.[3] For the variations in the thermal e.m.f., E, and in Peltier e.m.f., P, in a tungsten-lead circuit and for the coefficient of the Thompson effect in a tungsten wire, he has given the following equations for atmospheric pressure and temperatures between 0° and 100° C.:

$$E=(1.594t+0.01705t^2) \text{ microvolts} \tag{10}$$

$$P=(1.594+0.0341t)(t+273) \text{ microvolts} \tag{11}$$

$$\sigma=0.0341(t+273)\ \frac{\text{microvolts}}{\text{degree}} \tag{12}$$

Variations of E, P, and σ with pressure P for $O<P<12{,}000$ kg wt./cm² are shown in Table III for three temperatures.

Deviation from Lambert's cosine law.—Fulfilment of Lambert's cosine law for luminous radiation requires that an element of the light-source shall appear equally bright from whatever angle viewed. A black body fulfils this requirement. Tungsten deviates,[4] however, in that as the angle of viewing the surface changes from normal incidence to grazing incidence, the brightness, at first slowly and then more rapidly, increases from the normal brightness to a

[1] Worthing, *ibid.*, **4**, 535, 1914.

[2] Worthing, *ibid.*, **5**, 445, 1915.

[3] *Proceedings of the American Academy of Arts and Science*, **53**, 269, 1918.

[4] Worthing, *Astrophysical Journal*, **36**, 345, 1912.

maximum brightness of about 115 per cent of normal at a 75° angle, after which it decreases rapidly and probably reaches zero at 90°

TABLE III

EFFECT OF PRESSURE ON THERMO-ELECTRIC PROPERTIES OF TUNGSTEN

PRESSURE	$t=0°$ C.		$t=60°$ C.			$t=100°$ C.		
kg wt./cm²	P μ-volts	$\frac{\sigma}{\text{μ-volts}}{\text{deg.}}$	E μ-volts	P μ-volts	$\frac{\sigma}{\text{μ-volts}}{\text{deg.}}$	E μ-volts	P μ-volts	$\frac{\sigma}{\text{μ-volts}}{\text{deg.}}$
2000.....	+ 5.9	+.020	+1.415	+ 8.7	+.025	+ 2.53	+10.4	+.028
4000.....	11.7	.045	2.87	17.1	.037	4.99	20.3	.026
6000.....	17.2	.085	4.30	27.1	.073	7.60	32.0	.057
8000.....	24.1	.057	5.72	34.4	.106	10.12	43.4	.146
10,000.....	30.4	.035	7.10	42.3	.143	12.61	55.4	.235
12,000.....	+35.7	+.093	+8.58	+51.8	+.151	+15.14	+64.8	+.198

E is the thermal e.m.f. of a couple composed of a branch of uncompressed metal and a branch of compressed metal, one junction being at 0° C., the other at temperatures indicated. A positive e.m.f. indicates tendency for current to pass from uncompressed to compressed metal at the hot junction.

P is the Peltier effect at a junction between the compressed and uncompressed branches. The plus sign indicates heat absorption at junction with passage of current from the uncompressed to the compressed branch.

σ is the excess of the Thompson coefficient in compressed over uncompressed metal.

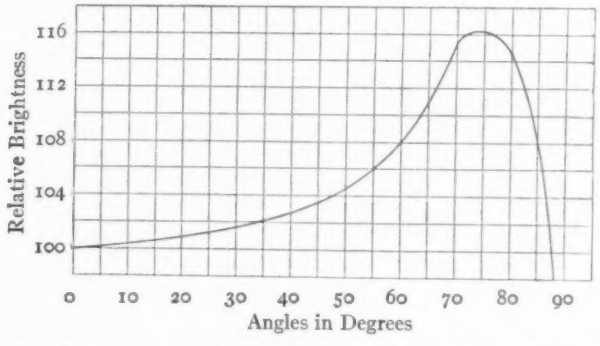


FIG. 6.—The deviation from Lambert's cosine law of the emission from tungsten at normal operating temperature.

(Fig. 6). The variation with wave-length is small but real, and whether or not there is a variation with temperature is not definitely determined.

Computation shows that the average brightness of a cylindrical tungsten-wire filament viewed normal to its length is about 3 per cent greater than the normal brightness, and that the average brightness, taking account of all direction of emission, as is done when the brightness is computed from the total light-output and filament dimensions, is about 5 per cent greater than the normal brightness. This correction must be taken into account when intercomparing the values for B_n, η, and efficiency values shown in Table I.

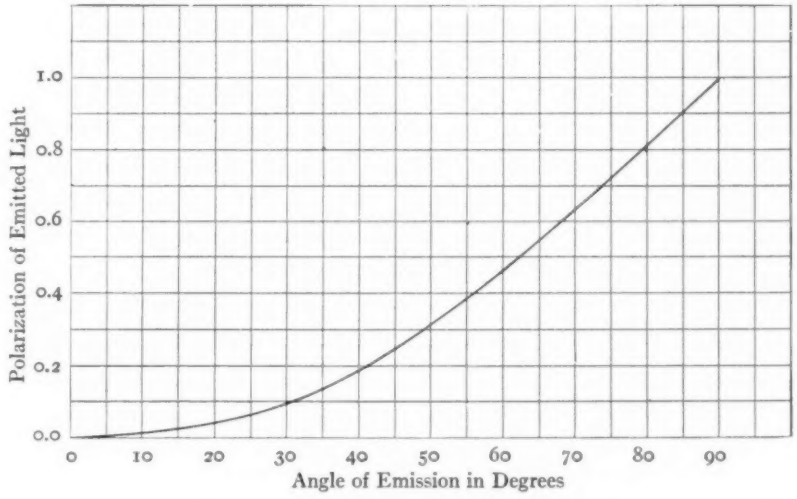


FIG. 7.—Polarization of the light emitted from tungsten at different angles of emission.

Polarization of light emitted.—The light emitted by tungsten in directions other than normal is polarized. The variation with angle of emission is shown in Figure 7. The direction of the electric vector of the stronger component of an emitted ray falls in the plane of emission, that is, the plane determined by the ray considered and the normal to the surface at the point of emission. For a straight tungsten filament of circular cross-section, as may be shown, the light emitted in a direction normal to its length is polarized by about 19 or 20 per cent. The direction of the electric vector of the stronger component is normal to the length of the filament.

Density.—The density of tungsten in wire form as ordinarily prepared is quite closely 19.3 g/cm³ at room temperature; as determined by X-Ray analyses[1] in ingot form it is somewhat less. Whether or not a variation occurs with continued drawing is uncertain.

Lattice spacing.—Tungsten crystals have a body-centered, cubic lattice. The edge of the elementary cube as determined by X-ray analysis[1] is 3.155 A. This is consistent with the above-given density, 184 (o = 16) as the atomic weight, and 1.663×10^{-24} g as the mass of the hydrogen atom.

Simple rigidity.—The rigidity[2] of tungsten varies greatly with wire size, grain structure, and temperature. Our knowledge regarding these variations is quite limited. Results that have been obtained indicate tungsten at room temperature to have the greatest rigidity of all substances recorded in the literature. Depending upon wire size and grain structure, variations in the modulus of rigidity between 0.9 and 2.2×10^{12} dynes/cm² (i.e., between about 9000 and 22,000 kg wt/mm²) have been found at room temperature. How much of the variation is to be ascribed to wire size, to grain structure, or to impurities is uncertain.

The variation with wire size consists of an increase in the modulus with a decrease in the diameter. The results at room temperature obtained with variations in grain structure seem confused. The temperature variations, however, are more definite. Starting at room temperature, there seems first to be a relatively slow decrease in the rigidity modulus amounting only to about 5 per cent in going to 1000° K. and then gradually a much higher rate of decrease so that at 2000° K. it is only about 15 per cent of the room-temperature value (Fig. 8). The three curves represent successive runs on the same specimen of wire. They show unexplained variations, a part of which are probably due to changes in grain structure.

Young's modulus.—Very little data on Young's modulus[3] for

[1] Hull, *Physical Review*, **17**, 576, 1921; Davey, letter.

[2] Sieg, *Physical Review*, **9**, 337, 1917; Worthing, *ibid.*, **12**, 219, 1918; Schriever, *ibid.*, **20**, 96, 1922; W. Giess, *Physica*, **3**, 322, 1923.

[3] Fink, *Transactions of the Electrochemical Society*, **22**, 503, 1912; Dodge, *Physical Review*, **11**, 311, 1918; Schonborn, *Zeitschrift für Physik*, **8**, 377, 1922; Worthing, *Physical Review*, **12**, 219, 1918; W. Giess, *Physica*, **3**, 322, 1923.

tungsten are available. Results published, however, indicate that tungsten at room temperature has the highest modulus of all substances recorded in the literature. Values varying from 3.40 to 4.15×10^{12} dynes/cm² (i.e., from about 35,000 to about 42,000 kg wt./mm²) have been found. Probably the variations with grain structure and wire diameter are of the same order as with the rigidity modulus. The variation of Young's modulus with temperature has not been carried as far as it has been in the measurements of the rigidity modulus; but, in going from room temperature to 1300° K., the upper limit at which experiments were made, a

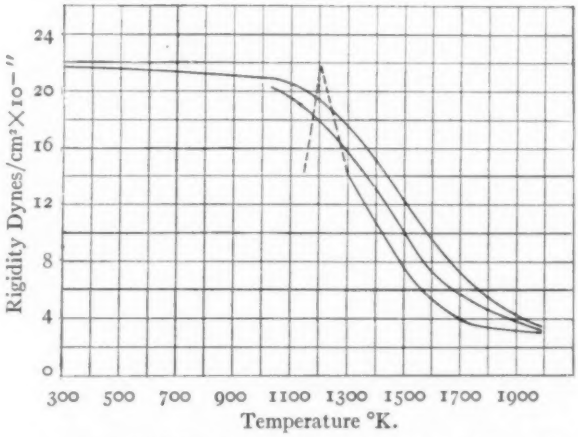


FIG. 8.—Rigidity of tungsten as a function of temperature

similar slow decrease (amounting in this case to a little less than 10 per cent) was found.

Compressibility.—Values for the compressibility of tungsten are taken from a paper by Bridgman.[1] He used two specimens, *A*, swaged but not drawn, with a diameter of 0.48 cm; and *B*, swaged and drawn with a diameter of 0.051 cm. Tests at 30° C. and 75° C. were made. The temperature variation was very small. For 30° C. he gives

$$\frac{\Delta v}{v_0} = -10^{-7}(2.93 - 1.5 \times 10^{-5} p)p \qquad (13)$$

$$\frac{\Delta v}{v_0} = -10^{-7}(3.15 - 1.6 \times 10^{-5} p)p, \qquad (14)$$

[1] *Proceedings of the American Academy of Arts and Science*, **58**, 165, 1923.

where $\frac{\Delta v}{v_0}$ represents the fractional change in volume and p the pressure in kg wt./cm².

For the compressibility $-\frac{1}{v}\frac{dv}{dp}$, the foregoing give at room temperature 2.93×10^{-7} and 3.15×10^{-7} $\frac{1}{\text{kg wt./cm}^2}$. The bulk moduli, $-v\frac{dp}{dv}$, which follow are 3.34×10^{12} dynes/cm² and 3.11×10^{12} dynes/cm². For comparison two other values 2.77×10^{12} dynes/cm² at 300° K. and 3.55×10^{12} dynes/cm² are taken from a paper by one of the present authors.[1]

TABLE IV

TENSILE STRENGTH OF TUNGSTEN

KIND OF MATERIAL	DIAMETER		TENSILE STRENGTH	
	Mils	Millimeters	lb. wt./in.²	kg wt./mm²
Sintered tungsten ingot	200 by 250	.....	18,000	13
Swaged rod	216	5.49	50,600	36
Swaged rod	125	3.18	107,000	75
Swaged rod	80	2.03	176,000	124
Swaged rod	26	.660	215,000	151
Drawn wire	18.0	.457	264,000	186
Drawn wire	7.23	.184	340,000	239
Drawn wire	5.78	.147	366,000	257
Drawn wire	5.50	.139	378,000	266
Drawn wire	3.96	.101	483,000	340
Drawn wire	1.14	.029	590,000	415

Tensile strength and reduction of area at break.—Other elastic constants of particular interest in the metallurgy of tungsten are the tensile strength and the reduction of area at the point of break. Results here given are taken from papers by Dr. Zay Jeffries.[2] Tensile strengths at room temperature given in Table IV refer only to swaged rods and drawn wire obtained from one particular ingot, and for these reasons are believed to show purely the effects of variation in wire size. Variations in tensile strength and reduction of area at break for various temperatures are shown in Figures 9 and 10 for four wire specimens having approximately the same diameters but different heat treatments.

[1] Worthing, *Physical Review*, **12**, 219, 1918.

[2] *Amer. Inst. Mining Met. Eng.*, **138**, 1037, 1918; *ibid.*, **146**, 575, 1919.

Hardness.—The data on hardness given in Table V were furnished by Dr. Samuel L. Hoyt, of the Research Laboratory of the General Electric Company at Schenectady.

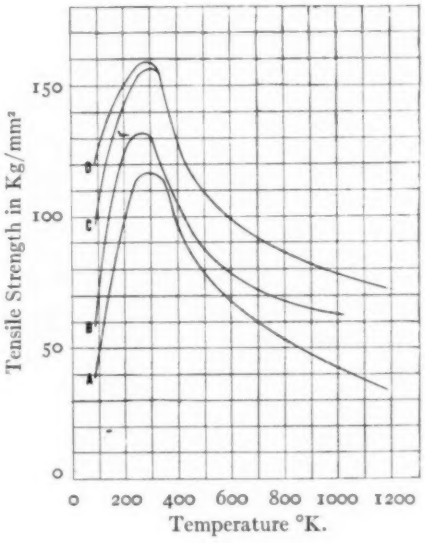


FIG. 9.—Tensile strength of tungsten as a function of temperature. (*A*) 4.2 mm rod swaged to 0.76 mm and drawn to 0.63 mm at temperatures changing gradually from 1580° K. to 1280° K. and then equiaxed. (*B*) 1.07-mm equiaxed rod drawn at 1280° K. to 0.71 mm. (*C*) 3.18-mm equiaxed rod swaged at 1280° K. to 0.76 mm and then drawn at same temperature to 0.64 mm. (*D*) 4.2-mm rod swaged to 0.76 mm and drawn to 0.63 mm at temperatures changing gradually from 1580° K. to 1280° K. but not equiaxed.

TABLE V

HARDNESS OF TUNGSTEN

Sample Number	Sample	Rockwell, "C"	Scleroscope
1.....	1-in. ingot	20	45
2.....	Same as No. 1 swaged to $\frac{3}{4}$ in.:		
	a=surface	39	55–56
	b=center	23	35?
3.....	Swaged tungsten	45	83
4.....	Tool-steel comparison	61	95

Sample No. 2 gave a Brinell number of 350, but the impression showed fine cracks around it, so the figure may be a little in error.

CHARACTERISTICS OF TUNGSTEN LAMPS

Temperature, voltage, candle-power relations for vacuum lamps.—The variation of the candle-power and wattage of vacuum tungsten lamps has been studied[1] over a wide range of voltage and results given in percentages of the normal values. From the known

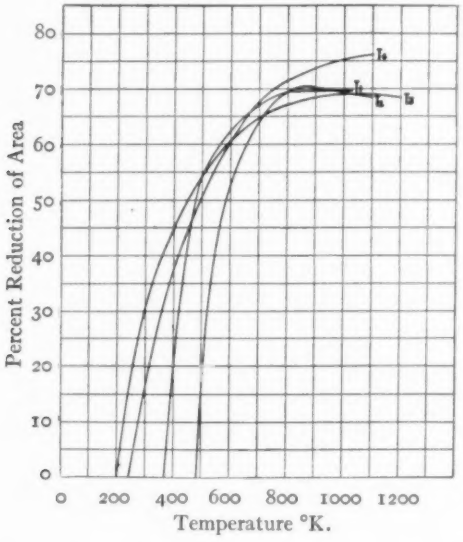


FIG. 10.—Reduction of area of tungsten wires at break as a function of temperature. T_1, 1.07-mm equiaxed rod drawn at 1280° K. to 0.71 mm. T_2, 4.2-mm rod swaged to 0.76 mm and drawn to 0.63 mm at temperatures changing gradually from 1580° K. to 1280° K. and then equiaxed. T_3, 3.18-mm equiaxed rod swaged at 1280° K. to 0.76 mm and then drawn at same temperature to 0.64 mm. T_4, 4.2-mm rod swaged to 0.76 mm and then drawn to 0.63 mm at temperatures changing gradually from 1580° K. to 1280° K. but not equiaxed.

relation between luminous efficiency and temperature,[2] these values have been arranged to show their dependence upon temperature. The values given in Table VI were obtained from ordinary lamps, and have not been corrected for end losses.

[1] Cady, *Electrical Review and Western Electrician*, **59**, 1092, 1911; Middlekauff and Skogland, *Bulletin of the Bureau of Standards*, **11**, 484, 1914; Shackelford, "Pyrometer Symposium," *Amer. Inst. Mining Met. Eng.*, p. 627, 1920.

[2] Hyde, Cady, and Forsythe, *Physical Review*, **10**, 401, 1917.

A factor, the approximate value of which is very useful for predicting variations due to small changes in operating conditions, is

TABLE VI

CHARACTERISTICS OF VACUUM TUNGSTEN LAMPS AS A FUNCTION OF TEMPERATURE

Temperature Maximum, K.	Color-Temperature Average, K.	Luminous Efficiency Lumens per Watt	Brightness Candles per cm²	Percentage Volts	Percentage Watts	Percentage Current	Percentage Candle-Power	$\frac{V}{c\phi}\frac{d c\phi}{dV}$	Percentage Life L	$\frac{T}{L}\frac{dL}{dT}$
2000°	2024°	2.50	20.0	55.0	38.7	70.3	10.4	4.1	1,090,000.	−53
2100..	2128	3.65	35.6	63.6	48.7	76.5	18.6	3.9	100,100.	50
2200..	2231	5.00	61.3	73.3	61.1	83.3	32.2	3.8	11,400.	48
2300..	2335	6.70	100.5	83.5	75.2	90.0	52.2	3.6	1490.	46
2400..	2440	8.50	157.0	95.0	92.1	97.0	82.9	3.5	246.	44
2450..	2493	9.8	193.0	100.0	100.0	100.	100.0	3.4	100.	43
2500..	2546	10.8	237.5	105.9	109.6	103.5	122.0	3.4	45.	42
2600..	2652	13.2	347.	118.5	130.6	110.3	179.3	3.3	9.4	40
2700..	2758	15.8	498.	132.3	155.6	117.6	257.0	3.2	2.3	−38

that represented by the ratio of a percentage change in current to the accompanying percentage change in voltage:

$$\frac{V}{I}\frac{dI}{dV}=D. \tag{15}$$

For tungsten D may be taken as roughly constant and equal to 0.6. Other corresponding percentage changes follow:

$$\frac{V}{W}\cdot\frac{dW}{dV}=1+D=1.6 \tag{16}$$

$$\frac{V}{R}\cdot\frac{dR}{dV}=1-D=0.4. \tag{17}$$

To illustrate: If a 110-volt lamp is operated at a 1 per cent increase in voltage, the consequent increases in current, wattage, and resistance are roughly 0.6, 1.6, and 0.4 per cent.

Dependence of current, voltage, etc., upon filament dimensions.—For the comparison of performances of different-sized filaments and for the planning of special lamps or experimental set-ups using tungsten filaments, the following considerations which apply to vacuum conditions only are given. End-loss effects are ignored.

The relations sought depend upon the elementary equations,

$$W = 2\pi r \eta L \tag{18}$$

$$R = \frac{\rho L}{\pi r^2} \tag{19}$$

$$V = \rho \frac{I}{\pi r^2} \cdot L \,, \tag{20}$$

where W, R, I, and V have their usual significance of wattage, resistance, current, and voltage, and η, ρ, r, and L refer, respectively, to radiation intensity, resistivity, filament radius, and filament length. For various conditions of comparison of two filaments designated by the subscript following the brackets, these equations lead to several simple relations of which the following are generally the most useful:

$$\left[\frac{I_1}{I_2} = \left(\frac{r_1}{r_2}\right)^{\frac{3}{2}}\right]_{T_1 = T_2} \tag{21}$$

$$\left[\frac{V_1}{V_2} = \left(\frac{r_2}{r_1}\right)^{\frac{1}{2}} \frac{L_1}{L_2}\right]_{T_1 = T_2} \tag{22}$$

$$\left[\frac{W_1}{W_2} = \frac{r_1 L_1}{r_2 L_2}\right]_{T_1 = T_2} \tag{23}$$

$$\left[\frac{r_1}{r_2} = \left(\frac{L_1}{L_2}\right)^2 = \left(\frac{W_1}{W_2}\right)^{\frac{2}{3}} = \left(\frac{I_1}{I_2}\right)^{\frac{2}{3}}\right]_{\substack{T_1 = T_2 \\ V_1 = V_2}} \tag{24}$$

$$[I_1 V_1^3 = I_2 V_2^3]_{\substack{T_1 = T_2 \\ L_1 = L_2}} \cdot \tag{25}$$

Knowing the current required to heat a certain-sized wire to a specified temperature, equation 21 shows how to obtain the current required to heat any other sized wire to the same temperature. Similarly, equation 24 shows the variations in the dimensions of filaments which must occur in order that the filaments shall operate at the same voltage and temperature, while equation 25 shows the conditions for operating a given filament so that, as it vaporizes, its temperature shall remain constant, provided that the character of a filament surface does not change materially during continued operation.

Simple-design equations may be obtained from equations 18 and 19. They are:

$$L=\left(\frac{IV^3}{4\pi\rho\,\eta^2}\right)^{\frac{1}{3}} \tag{26}$$

$$r=\frac{IV}{2\pi\eta\,L}. \tag{27}$$

To determine, for instance, the dimensions of a filament, supported by its leads only, which shall operate at 10 volts and 1 amp. and yield a temperature of 2400° K., it is necessary, first, to find from Table I values of η and ρ corresponding to 2400° K., and then to substitute these values in the equations. In this instance the length is 6.9 cm and the radius is 0.040 mm. To take account of the end-loss corrections, as shown by equation 29, the total length should be increased by $2\,\Delta L_B$, in this case by 0.47 cm. The foregoing refers only to operation after the initial seasoning.

In Table VII are given the currents necessary to heat various-sized filaments to different temperatures and also the voltage gradients for filaments of different radii at different temperatures. The values given apply to uniformly heated parts of the filaments. If an attempt is made to calculate lengths for various voltages or the voltage for a definite length from these data, corrections must be made for the end cooling (see equation 29).

Wire weight.—When speaking of the size of tungsten wire, it is customary to give the weight in milligrams of a 200-mm length rather than the diameter. Table VIII has been prepared to show the relation between the wire weight and the radius in both centimeters and mils. The value, 19.3, has been used as the density.

Photographic effects.—The photographic effects[1] given apply only to orthochromatic plates. The values given in Figure 11 are for the relative photographic effectiveness at various temperatures for constant illumination through lead glass. This is equivalent to the relative plate speeds, i.e., the reciprocal of the time required to produce equal blackening of the plate.

Life of lamps.—The life of a vacuum tungsten lamp is a function of two factors: the temperature of operation and the wire size. The

[1] Luckiesh, Holliday, and Taylor, *Journal of Franklin Institute*, **196**, 495, 1923.

TABLE VII*

CURRENT. I, IN AMPERES AND POTENTIAL GRADIENT, dV/dL, IN VOLTS PER CENTIMETER FOR VARIOUS-SIZED TUNGSTEN FILAMENTS AT DIFFERENT TEMPERATURES

Temperature, ° K.	Radius in Centimeters	.001	.002	.003	.005	.008	.010	.015	.020	.030	.050	.080	.100
1000	I =	.022	.63	.116	.250	.51	.70	1.32	2.00	3.80	8.0	16.0	22.0
	dV/dL =	.184	.130	.107	.083	.065	.058	.047	.041	.034	.026	.021	.018
1200	I =	.032	.092	.167	.365	.73	1.03	1.88	2.90	5.3	11.4	23.0	32.0
	dV/dL =	.325	.230	.188	.148	.115	.103	.084	.073	.060	.046	.036	.033
1400	I =	.045	.127	.235	.50	1.02	1.42	2.60	4.00	7.4	15.9	32.0	45.0
	dV/dL =	.55	.385	.315	.245	.194	.173	.141	.122	.100	.078	.061	.055
1600	I =	.059	.167	.305	.66	1.33	1.86	3.40	5.3	9.7	21.0	42.0	59.
	dV/dL =	.85	.60	.485	.374	.300	.265	.215	.188	.153	.119	.094	.084
1800	I =	.074	.207	.385	.82	1.66	2.35	4.25	6.6	12.1	26.0	53.	74.
	dV/dL =	1.23	.87	.71	.55	.435	.385	.315	.275	.225	.174	.130	.123
2000	I =	.090	.255	.465	1.00	2.02	2.85	5.2	8.0	14.7	31.5	65.	90.
	dV/dL =	1.70	1.20	.98	.76	.60	.54	.440	.380	.310	.240	.190	.170
2100	I =	.098	.275	.51	1.09	2.20	3.10	5.7	8.7	16.1	34.5	70.	98.
	dV/dL =	1.96	1.39	1.14	.88	.69	.62	.50	440	.360	.280	.220	.196
2200	I =	.106	.300	.55	1.19	2.40	3.35	6.2	9.5	17.4	37.5	76.	106.
	dV/dL =	2.25	1.59	1.30	1.01	.80	.71	.58	.50	.410	.320	.250	.225
2300	I =	.115	.325	.60	1.29	2.61	3.65	6.7	10.3	18.9	41.0	82.	115.
	dV/dL =	2.56	1.80	1.47	1.15	.90	.81	.66	.57	.465	.360	.285	.255
2400	I =	.124	.350	.65	1.39	2.80	3.90	7.2	11.1	20.5	44.0	89.	124.
	dV/dL =	2.90	2.05	1.68	1.30	1.03	.92	.75	.65	.53	.410	.325	.290
2500	I =	.133	.375	.69	1.49	3.00	4.20	7.7	11.9	21.8	47.0	95.	133.
	dV/dL =	3.28	2.32	1.90	1.47	1.16	1.04	.85	.73	.60	.465	.365	.330
2600	I =	.143	.400	.74	1.59	3.20	4.50	8.2	12.7	23.5	50.0	102.	143.
	dV/dL =	3.65	2.60	2.10	1.64	1.30	1.16	.95	.82	.67	.52	.410	.370
2700	I =	.152	.430	.79	1.70	3.45	4.80	8.8	13.6	25.0	54.	109.	152.
	dV/dL =	4.109	2.90	2.35	1.84	1.45	1.29	1.06	.92	.75	.58	.460	.410
2800	I =	.162	.460	.84	1.81	3.65	5.1	9.4	14.5	26.5	57.	116.	162.
	dV/dL =	4.55	3.20	2.65	2.05	1.61	1.44	1.18	1.02	.83	.64	.51	.455
2900	I =	.172	.485	.89	1.92	3.90	5.4	10.0	15.4	28.0	61.	123.	172.
	dV/dL =	5.0	3.55	2.90	2.25	1.78	1.59	1.30	1.12	.92	.71	.56	.50
3000	I =	.182	.52	.95	2.05	4.10	5.8	10.6	16.4	30.0	64.	130.	182.
	dV/dL =	5.6	3.95	3.20	2.50	1.97	1.76	1.43	1.24	1.01	.78	.62	.56

* These values of the voltage gradients apply to the uniformly heated parts of the filaments. See Table I, *C*. To take account of the cooling due to two leads, a computed length should be increased by $2\,\Delta L_B$ (see equation 29).

temperature through determining the rate of vaporization is by far the more important factor. Empirically the average life,

TABLE VIII

WEIGHT IN MILLIGRAMS OF 200-MILLIMETER LENGTHS AND RESISTANCE IN OHMS OF 1-CENTIMETER LENGTHS OF TUNGSTEN WIRE FOR VARIOUS RADII GIVEN IN CENTIMETERS AND MILS. THE VALUE, 19.3 G/CM³, HAS BEEN USED AS THE DENSITY IN THE CALCULATIONS

Radius cm	Weight of 200-mm Length mg	Resistance of 1 cm of Wire Ohms	Radius mils	Weight of 200-mm Length mg	Resistance of 1 cm of Wire Ohms
.001	1.21	1.745*	0.5	1.96	1.080*
.002	4.85	.436	1.	7.82	.2705
.003	10.91	.1935	2.	31.3	.0675
.004	19.40	.1085	3.	70.4	.0301
.005	30.3	.0698	4.	125.2	.01690
.006	43.7	.0485	5.	195.5	.01075
.007	59.2	.0356	6.	287.	.00751
.008	77.6	.0273	7.	383.	.00552
.009	98.2	.0215	8.	501.	.00423
.010	121.2	.01745	9.	634.	.00334
.015	273.	.00775	10.	782.	.002705
.020	485.	.00436	15.	1760.	.001205
.050	3030.	.000698	20.	3130.	.000675

* These values apply to well-seasoned wire at 20°C. For wire that is not seasoned, values as much as 50 per cent higher may be obtained, depending upon the method of production.

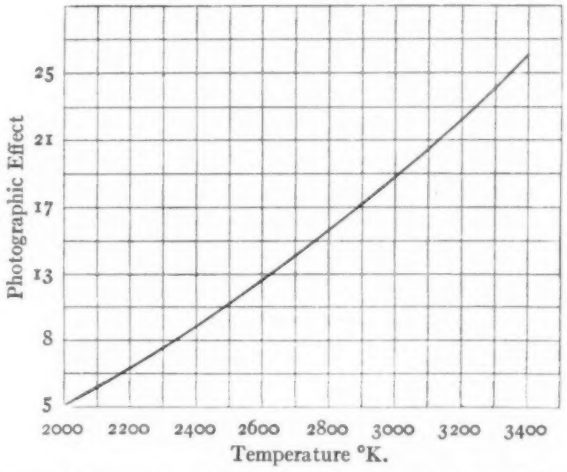


FIG. 11.—Photographic effect for tungsten at equal illumination for different temperatures.

whatever the diameter, has been found to coincide with the period of burning required for the reduction by vaporization of the original

| | | |

diameter by a given percentage. Since, with an increased diameter, there is an increased thickness of layer to be vaporized during life, there is also an increased life, if the temperature of operation is not changed, and hence the dependency on filament diameter. Values given in Table VI obtained from the vaporization rate[1] are relative, and show only the variation with temperature. The unit of life is taken as 1000 hours at 2450° K. This corresponds approximately to the case of the commercial 25-watt, 115-volt

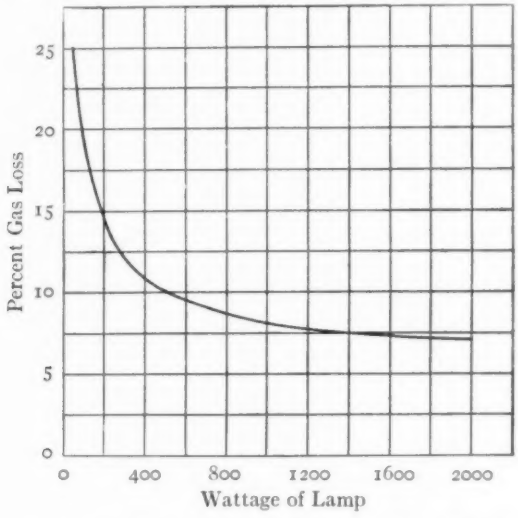


FIG. 12.—Percentage gas loss for different wattage gas-filled lamps

vacuum lamp. Values in Table XI show results for many commercial lamps, taking account of both factors.

Gas losses.—By operating the filament of a tungsten lamp in an atmosphere of an inert gas, the rate of vaporization is enormously reduced, thus permitting the filament to be operated at a much higher temperature for the same life. There is a loss of energy due to the conduction and convection of heat by the gas. This loss of heat has been found to depend upon the size of the filament, being much smaller for large filaments. If the filament is coiled into a helix,[2] the energy losses depend upon the diameter of the

[1] Langmuir, *Physical Review*, **2**, 329, 1913.

[2] *Ibid.*, **34**, 401, 1912.

helix. The gas loss[1] as a function of the wattage of the lamp containing a mixture of argon and nitrogen as used in ordinary gas-filled lamps is shown in Figure 12.

End losses.—Incandescent-lamp filaments are cooled by the lead and support wires. As a result, the input of energy as well as the outputs of radiant energy, luminous flux, and thermionic emission are diminished. These reductions are summed up as end losses.[2]

TABLE IX

VALUES OF Q, $\sqrt{2\rho\eta}/Q$, AND VARIOUS EFFECTIVE VOLTAGE CORRECTIONS FOR VARIOUS MAXIMUM TEMPERATURES, T_m, FOR USE WITH EQUATIONS 28–37 IN COMPUTING END LOSSES. THE JUNCTION TEMPERATURE IS ASSUMED TO BE $T_m/4$

Temperature, K.	Q cm$^{-\frac{1}{2}}$	$\sqrt{2\rho\eta}/Q = \Delta V_B$ Volts	ΔV_C Volts	ΔV_D Volts	ΔV_E Volts
1000°	.079	.066	.15	.20	.26
1200	.116	.089	.20	.27	.34
1400	.156	.112	.25	.34	.43
1600	.196	.137	.31	.41	.54
1800	.238	.162	.36	.49	.62
2000	.284	.189	.42	.57	.73
2200	.328	.217	.49	.65	.84
2400	.375	.246	.55	.74	.95
2600	.422	.276	.62	.83	1.06
2800	.470	.308	.69	.92	1.18
3000	.519	.340	.76	1.02	1.31
3200	.569	.374	.84	1.12	1.44

There are three methods of eliminating or correcting for end losses. The first employs very fine-wire volt connections to points on the filament at a known distance apart, but far enough removed from the cooling leads or supports so that the part included will be at a uniform temperature. In the second method two filaments of the same diameter but of different known lengths are mounted on

[1] Van Horn, "Pyrometer Symposium," *Amer. Inst. Mining Met. Eng.*, p. 638, 1920.

[2] Worthing, *Journal of Franklin Institute*, **194**, 597, 1922; Hyde, Cady, and Worthing, *Trans. Illuminating Engineering Society*, **6**, 238, 1911. See also, Amrine, *ibid.*, **8**, 385, 1913; Stead, *Journal of the Institution of Electrical Engineers* (England), **58**, 107, 1920.

the same stem, the short one being long enough so that the temperature of its central part is not affected by end losses. The differences in voltage, light-output, etc., for the two filaments for the same current are the voltage drop, light-output, etc., for a uniformly heated filament, the length of which is the difference in lengths of the two filaments. The third method depends upon measuring the variations in brightness of the filament from the uniformly heated part to the lead, and, from the temperature distribution thus obtained, computing the end-loss effects. All three methods have been used in determining the results reported in Tables IX

TABLE X*

Temperature, K.	Radius in Centimeters												
	.001	.002	.003	.005	.008	.010	.015	.020	.030	.050	.080	.100	.500
1000°.....	3.	4.	5.	6.	8.	9.	11.	12.	15.	20.	25.	28.	65.
1200.....	2.	3.	3.5	4.0	5.5	6.0	7.5	8.5	10.	13.	17.	19.	42.
1400.....	1.5	2.0	2.5	3.0	4.0	4.5	5.5	6.5	8.0	10.	13.	14.	32.
1600.....	1.1	1.6	2.0	2.5	3.2	3.6	4.4	5.1	6.2	8.0	10.	11.	25.
1800.....	.9	1.3	1.6	2.1	2.7	2.96	3.6	4.2	5.1	6.6	8.4	9.5	21.
2000.....	.8	1.1	1.4	1.7	2.2	2.47	3.0	3.5	4.3	5.5	7.0	8.0	17.
2200.....	.68	.96	1.2	1.5	1.9	2.15	2.6	3.0	3.7	4.8	6.1	6.8	15.
2400.....	.59	.84	1.0	1.3	1.7	1.88	2.3	2.7	3.2	4.2	5.3	5.9	13.
2600.....	.52	.74	.90	1.17	1.48	1.66	2.0	2.3	2.9	3.7	4.7	5.3	12.
2800.....	.47	.67	.82	1.06	1.33	1.50	1.8	2.1	2.6	3.3	4.2	4.7	11.
3000.....	.42	.60	.74	.95	1.21	1.35	1.7	1.9	2.3	3.0	3.8	4.3	10.
3200.....	.39	.55	.67	.87	1.10	1.23	1.5	1.7	2.1	2.8	3.5	3.9	9.

* Distance in centimeters from leads for various-sized long tungsten filaments, and various maximum temperatures, to points where the temperatures are only 0.1 per cent less than the maximum temperature ($7.0\sqrt{r}/Q$). For temperatures 0.01 per cent less the distances are 4/3 those given; for temperatures 1 per cent lower than the maximum the distances are 2/3 those given. For short filaments the filament half-lengths are about 13 per cent greater.

and X, but, for the most part, the end-loss corrections shown were determined by the third method.

Figure 13 shows the variations occurring in temperature A, resistance B, radiation intensity C, brightness D, and thermionic emission E in a long, straight tungsten filament ($r=0.01$ cm) near a cooling lead in a vacuum lamp when the central maximum temperature is 2400° K. Distribution curves corresponding to any other maximum filament temperature and filament radius may be obtained from these curves by increasing all abscissae by the ratio of $[Q/\sqrt{r}]_0$ to $Q/\sqrt{r}$, where r is the radius and Q is a function of the maximum temperature and of certain properties of tungsten at this

temperature. The fraction $Q\sqrt{r}$ (see Table IX) refers to the conditions sought and $[Q\sqrt{r}]_0$ to the condition diagrammed in Figure 13.

In Figure 13 the areas between the curves, the y-axis, and the line $y=1.0$ represent end losses. In the case of curve B, suppose a line drawn at about $L=0.27$ cm; then the area below the curve and to the left of this line will be found equal to that part of the end-loss area above this curve and to the right of this line. Thus there is an effective filament shortening, ΔL_B, in this case which

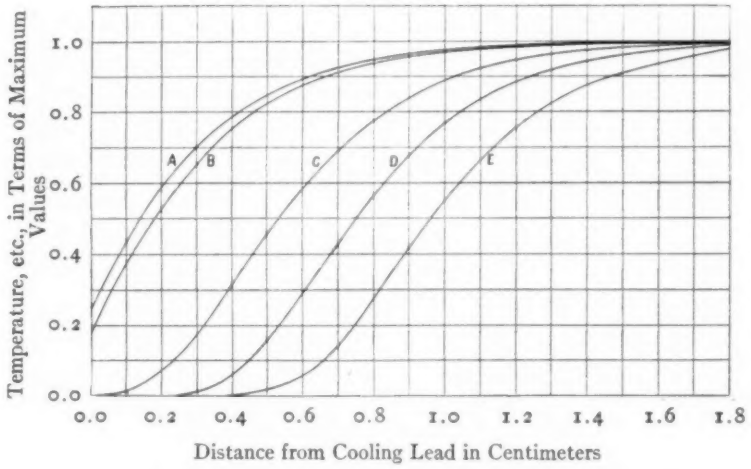


FIG. 13.—Various distribution curves near a cooling junction for a long tungsten wire ($r=0.01$ cm.) electrically heated *in vacuo* to a central maximum temperature of 2400° K. (*A*) temperature; (*B*) resistance; (*C*) radiation intensity; (*D*) brightness; (*E*) thermionic emission intensity.

amounts to 0.27 cm. This means that the resistance of the filament for the condition specified with the cooling leads is equal to the resistance of a uniformly heated filament which is 0.27 cm shorter for each junction of filament to lead wires. For curves C, D, and E, the effective filament shortenings, ΔL_C, ΔL_D, and ΔL_E, are about 0.60, 0.80, and 1.04 cm. Effective filament shortenings vary with filament radius, maximum filament temperature, and the property (e.g., energy input, etc.) studied.

The difference between the supply rate and the radiation rate near a cooled support or lead is the rate of conduction of heat to it.

This heat-conduction loss is represented in Figure 13 by the area between curves B and C. If the ordinates are expressed in watts per cm of filament length, the heat-conduction loss is given directly in watts. For the case represented, it is the wattage of a portion of the uniformly heated filament whose length is 0.33 cm, the difference between the effective shortenings, 0.60 cm and 0.27 cm. In general, this loss is given relatively by $\frac{\Delta L_C - \Delta L_B}{L}$, where L is the filament half-length. Equations that follow may be used for its evaluation.

The effective filament shortenings from the various standpoints are given by

$$\Delta L_A = 0.88\sqrt{r}/Q \quad \text{(heat content)} \tag{28}$$

$$\Delta L_B = 1.00\sqrt{r}/Q \quad \text{(energy input, voltage, or resistance)} \tag{29}$$

$$\Delta L_C = 2.25\sqrt{r}/Q \quad \text{(radiation output)} \tag{30}$$

$$\Delta L_D = 3.00\sqrt{r}/Q \quad \text{(light-emission)} \tag{31}$$

$$\Delta L_E = 3.85\sqrt{r}/Q \quad \text{(thermionic emission)}. \tag{32}$$

These equations show that all shortenings vary directly as $\sqrt{r}$ and inversely as Q (Table IX), a function of the maximum temperature. These equations give end-loss corrections directly when the filament's length, radius, and maximum temperature are known.

When the filament length and radius have not been measured directly, the end-loss corrections may be obtained from a consideration of the effective voltage corrections,[1] ΔV_A, etc., corresponding to the various standpoints. Limiting consideration to the case of a filament with only two leads, and representing by L, V, etc., the filament half-length, half the observed voltage, etc., these effective voltage corrections become the difference between the voltage drop over L, were it uniformly heated throughout, and the voltage drop over a shortened length of uniformly heated filament yielding the observed radiation, or luminous or thermionic output. These shortened lengths are $(L-\Delta L_A)$, etc. The voltage corrections sought are the products of ΔL_A, ΔL_B, etc., by dV/dL for a uni-

[1] Langmuir, *Transactions Faraday Society*, **17**, 621, 1922.

formly heated filament. Since dV/dL equals $\sqrt{2\rho\eta/r}$, where ρ is the resistivity and η the total radiation intensity, from equations 28 to 32 there follow:

$$\Delta V_A = 0.88\sqrt{2\rho\eta/Q} \quad \text{(heat content)} \tag{33}$$

$$\Delta V_B = 1.00\sqrt{2\rho\eta/Q} \quad \text{(energy input, voltage, or resistance)} \tag{34}$$

$$\Delta V_C = 2.25\sqrt{2\rho\eta/Q} \quad \text{(radiation output)} \tag{35}$$

$$\Delta V_D = 3.00\sqrt{2\rho\eta/Q} \quad \text{(light-emission)} \tag{36}$$

$$\Delta V_E = 3.85\sqrt{2\rho\eta/Q} \quad \text{(thermionic emission).} \tag{37}$$

These corrections (Table IX) depend upon the maximum temperature T, but not upon dimensions of the filament.

Empirically the variation of ΔV_B with T_m is closely given by

$$\Delta V_B = \tfrac{1}{2}(0.00028\,T_m - 0.17). \tag{38}$$

Other ΔV's can be represented by similar empirical equations. To illustrate the use of these equations and the table, suppose the thermionic-emission correction is desired for a filament with two leads between which there is a 10-volt drop and a central temperature of 2800° K. The factor "f" by which the observed thermionic emission must be multiplied to obtain the emission were the filament uniformly heated throughout its length is given by

$$\text{"}f\text{"} = \frac{L}{L-\Delta L_E} = \frac{L\dfrac{dV}{dL}}{(L-\Delta L_E)\dfrac{dV}{dL}} = \frac{V+\Delta V_B}{V+\Delta V_B-\Delta V_E}. \tag{39}$$

Since for this case $V = 5$ volts, $\Delta V_B = 0.31$ volts, and $\Delta V_E = 1.18$ volts, the correction factor is 1.28.

From the value of "f" given by the first part of equation 39, i.e., $\dfrac{L}{L-\Delta L_E}$, it can be shown that the percentage end-loss corrections for different temperatures for filaments of the same size in similar lamps vary inversely as the values of Q given in Table IX. For different-sized filaments in similar lamps the percentage correction varies as $\sqrt{r}$. Thus, if the end-loss correction is known for 1 maxi-

mum temperature for a particular filament, such correction can be easily computed for other maximum temperatures and for filaments of different radii for lamps similarly constructed.

Distances along a filament from a cooling lead to points where the temperatures are within 0.1 per cent of those of the uniformly heated portions are given in Table X. If temperatures within 0.01 per cent are desired, take distances four-thirds times those given in the table. If temperatures within 1 per cent only are desired, take lengths two-thirds times those here listed. Since the temperature at the center of short filaments is lowered by the cooling of both leads, their half-lengths must be about 13 per cent greater than lengths given in the table, in order that their central temperatures shall not be more than these same percentages lower than the central temperatures of long filaments when heated by the same currents. Thus, for a filament with a 0.01-cm radius and a central temperature of 1800° K., a total filament length of twice 3.3 cm or 6.6 cm must be used in order that its central temperature shall not be more than 1°.8 lower than that of a long filament of the same cross-section heated with the same current. Distances for other properties may be obtained from their temperature relations.

Some indications of the energy input and light-output end losses for commercial lamps are of interest.[1] The ordinary 40-watt, 115-volt vacuum tungsten lamp with a filament of 51 cm long and 0.038 mm in diameter has two large copper leads and eleven small molybdenum hook supports. The temperature is about 2450° K. While the lead-junction temperature is only a little greater than $T_m/4$, the support temperatures are considerably greater, about 1750° K. Because of this high value, equations 28–38 cannot be applied directly. By graphical means employing the curves of Figure 13, their contribution to the total end losses may be computed. In this way, total effective shortenings from the energy-input and light-output standpoints of 1.1 and 5.2 cm have been found. These correspond to 2.2 and 10 per cent, whence there is a decrease in efficiency of 7.8 per cent.

Temperature, brightness, and efficiency of some commercial lamps.—In Table XI the temperature, efficiency, and brightness of some

[1] Worthing, *Journal of Franklin Institute*, **194**, 608, 1922.

vacuum tungsten lamps[1] for 1000-hour life are given. In Table XII some similar data, together with average color temperatures, are

TABLE XI

TEMPERATURE, EFFICIENCY, AND BRIGHTNESS OF VACUUM LAMPS

Lamp	Lumens per Watt	Maximum Temperature, K.	Maximum Brightness Candles/cm²
50-watt carbon	3.3	2115°	55
50-watt gem	4.0	2180	78
50-watt tantalum	4.9	2160	53
10-watt tungsten	7.7	2355	128
25-watt tungsten	9.8	2450	193
40-watt tungsten	10.0	2460	206
60-watt tungsten	10.1	2465	211

TABLE XII

TEMPERATURE, EFFICIENCY, AND BRIGHTNESS OF GAS-FILLED TUNGSTEN LAMPS

Lamp	Lumens per Watt	Maximum Temperature, K.	Average Color Temperature, K.	Maximum Brightness of Filament Candles/cm²
Regular gas-filled lamps:				
50-watt	10.0	2685°	2670°	469
75-watt	11.8	2735	2705	563
100-watt	12.9	2760	2740	605
200-watt	15.2	2840	2810	781
300-watt	16.3	2870	2840	862
500-watt	18.1	2930	2920	1015
1000-watt	20.0	2990	2980	1225
2000-watt	21.2	3020	3000	1350
Special lamps:				
1000-watt stereopticon	24.2	3185	3175	2065
900-watt movie	27.3	3290	3220	2660
10-kw	31.0	3350	3300	3050
30-kw	31.0	3350	3300	3050
Daylight lamps:				
200-watt	10.0	2860	.....	.....
500-watt	11.2	2960	.....	.....
Photographic:				
750-watt	.....	3065	.....	.....
1500-watt	.....	3105	.....	.....

given for present-day, gas-filled lamps. Efficiency as functions of wattage for regular 115-volt tungsten lamps, is also shown

[1] Forsythe, *General Electric Review*, **26**, 830, 1923.

in Figure 14. In the vacuum lamp, the variation is due to the increase in temperature permissible in the larger filaments for the same percentage of loss of filament during life by vaporization. In the gas-filled lamp, there is the additional variation resulting from percentage decrease in gas loss with increase in filament size (also coil diameter) as well as that due to an increase in operating temperature.

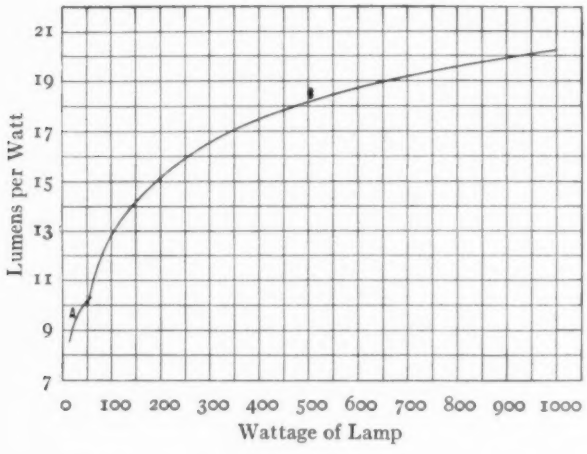


FIG. 14.—Efficiency of 115-volt tungsten lamps as a function of the wattage. Curve *A*, vacuum lamps; Curve *B*, gas-filled lamps.

Data on some special lamps are given in the second and third parts of the table. The 10- and 30-kw lamps were designed and constructed by the Lamp Development Laboratory of the National Lamp Works. They have four coils in the same plane covering an area 4×5 cm in the 10-kw lamp and 7×11 cm in the 30-kw lamp. The 10-kw lamp has a luminous intensity of about 40,000 candles in a direction perpendicular to the coils, while that for the 30-kw lamp is about 100,000 candles. This means that the 30-kw lamp gives the same illumination at a distance of $3\frac{1}{2}$ feet from the plane of the coils as does the sun in midsummer at noon.

Table XIII gives data on the brightness of the bulbs and filaments of some of the tungsten lamps with some other sources included for purposes of comparison.

TABLE XIII

BRIGHTNESS OF FILAMENTS AND BULBS OF SOME TUNGSTEN LAMPS AND OF SOME OTHER SOURCES FOR COMPARISON

Lamp	Brightness Measured at	Brightness Candles/cm²
Kerosene flame	Flat wick	1.2
4-watt per candle carbon lamp	Filament	55.0
40-watt vacuum tungsten lamp	Filament	206.
40-watt vacuum tungsten lamp	Bulb-frosted	2.5
40-watt golden Mazda	Bulb	2.0
50-watt white Mazda	Filament	408.
50-watt white Mazda	Bulb	1.3
75-watt white Mazda sprayed	Filament	563.
75-watt white Mazda sprayed	Bulb	2.1
2000-watt gas-filled Mazda	Filament	1350.
2000-watt gas-filled Mazda	Between coil	3000.
2000-watt gas-filled Mazda	Bulb-frosted	130.
Sun as observed at earth's surface	.....	165,000.
Clear sky, average	.....	0.4

In conclusion, the authors wish to express their appreciation of the help they have received from a number of their colleagues in the laboratories of the General Electric Company at Harrison, Schenectady, and Nela Park.

NELA RESEARCH LABORATORY
NATIONAL LAMP WORKS
CLEVELAND, OHIO
September 1924

A STUDY OF ELECTRICALLY EXPLODED WIRES[1]

By SINCLAIR SMITH

ABSTRACT

A new type of spectrograph.—The converging beam of light from a grating is reflected from one of the faces of a rotating mirror to the focal plane of the instrument. The rotation of the mirror causes the spectrum to move along a photographic film, and changes that take place in the spectrum of the light-source under investigation are recorded upon this film.

Time-resolving power.—The term "time-resolving power," analogous to optical-resolving power, is defined, and, for the instrument described, is shown to be about one one-millionth of a second.

Spectra.—The spectra of electrically exploded wires of various elements have been studied with the rotating-mirror spectrograph in the interval λλ 3000–5000, and results for *Pb*, *Sn*, *Al*, *Cu*, *Cd*, and *Mg* are described.

A new absorption phenomenon.—In the case of certain elements, small areas on the surface of the mass of vapor produced by an explosion proved to be very opaque for wave-lengths in the region studied. This absorption was not perfectly uniform, but showed irregularities in regions close to strong arc lines, which suggests that anomalous dispersion may explain the phenomenon.

The resistance of metallic vapors at high temperatures.—A method is described for determining the relative resistances of metallic vapors, and results are given for *Cu*, *Ag*, *Au*, *Ni*, *W*, *Zn*, *Al*, *Pb*, *Sn*, *Li*, and *Fe*.

Anderson[2] has shown that electrically exploded wires furnish spectroscopists with a source of metallic vapor at an exceedingly high temperature, and further that this vapor retains a high intrinsic brilliancy for a relatively long time after the excitation has ceased. As the spectrum shows a great variety of lines, the question naturally arises, Do all the lines appear simultaneously, or do different lines appear at different times? In order to answer this question, a new type of spectrograph was built which made possible the study of the variations of the spectrum with time.

METHODS AND APPARATUS

The spectrograph.—The essentially new feature of this spectrograph is a rotating mirror so mounted that the beam, after having passed through the slit and suffered dispersion, is reflected from one of the faces of the rotating mirror to the focal plane of the instrument. Two of these instruments were built, one with a prism and

[1] *Contributions from the Mount Wilson Observatory*, No. 285.

[2] *Mt. Wilson Contr.*, No. 178; *Astrophysical Journal*, **51**, 37, 1920.

the other a concave grating. The arrangement of the optical parts of the prismatic instrument is shown diagrammatically in Figure 1. Figure 2 shows the position of the photographic film relative to the rotating mirror. This kind of instrument should be faster than the one to be described, but though a number of good camera lenses were tried, no lens combination having the desired characteristics was available. What is needed is a combination which will accurately focus the desired range of spectrum on a plane perpendicular to the axis of projection. Since a range of about 100 A was the best that could be done with the lenses available, this form of instrument was abandoned and the concave grating-type was adopted.

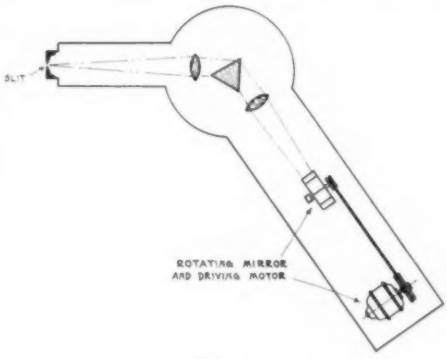


FIG. 1

The arrangement of the slit, grating, and rotating mirror is shown in Figure 3, while the position of the film relative to the rotating mirror is as before (see Fig. 2). A 4-inch, concave grating of 1-meter radius, having 15,000 lines per inch, was used. The slit was placed 2 meters from the grating, which fixed the distance from the grating to the focal plane at 66 cm, and gave in the first order a scale of 25 A per mm. The film was held in a circular holder having a 25-cm radius. The actual focal curve is not a circle, but a circle was found to be a sufficient approximation. The octagonal mirror was used to insure a record of every exposure. Since the film subtended an angle of slightly more than 90° as seen from the rotating mirror, the light from the grating always fell somewhere on the film, regardless of the position of the mirror.

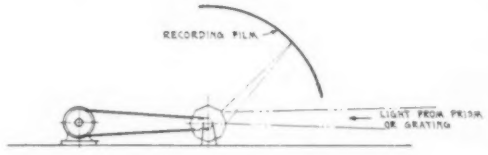


FIG. 2

When the instrument is in adjustment, the spectrum must of course be in focus; further, the rulings of the grating must be parallel to the slit and, at the same time, the projected slit images, i.e., the spectral lines, must be parallel to the direction in which they move when the mirror is rotated. The focusing can be done visually with a high-power lens, but the other conditions cannot be met so easily. The procedure adopted was as follows: The grating was first rotated to a position such that the central image would fall on the film. A film was then placed in the holder and exposed to a series

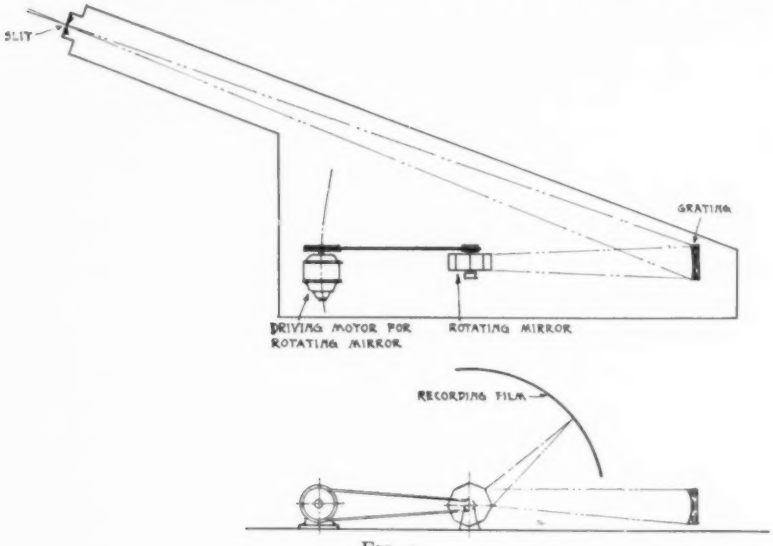


FIG. 3

of slit images with the mirror in different positions, and, finally, a reference line was put on the film by making a short exposure with the mirror slowly rotating. An arc was used for illumination. The parallel position was determined by measuring the inclination of the slit images to the reference line. This operation so oriented the slit that its projected image on the photographic film moved accurately along its own length when the mirror was rotated. The grating was then rotated back to its original position, and the normal adjusted. The rulings were made parallel to the slit by watching the spectral lines with a high-power lens and slowly rotating the grating about its normal.

Time-resolving power.—Since we shall be interested in determining differences in time as well as in wave-length, let us call the smallest time difference that can be measured the "time-resolving power" of the instrument. Since time differences are determined by measuring the distances along the time axis of the film from some arbitrary zero line to the two points in question, and multiplying the difference between these two distances by a factor (the time required for the image to move unit distance along the film), it might appear that the accuracy with which linear distances can be measured is the only limit to the determination of small time intervals. This, however, would be crediting the instrument with powers it does not possess. A consideration of optical-resolving power makes this clear. It is quite true that, regardless of the optical-resolving power of the spectrograph, the difference in wave-length of two spectral lines which are widely separated can be determined to the degree of accuracy with which we can measure the linear distance between them on the plate. If the two lines are very close together, however, the determination no longer depends on our ability to make close settings but on the resolving power of the instrument. For this reason we shall mean by time-resolving power, not the smallest measurable interval between the appearance of two different spectral lines, but rather the smallest measurable interval between changes that take place in some particular line. For example, suppose that a line disappears for a very short time and then reappears. If the interval of disappearance is less than the time-resolving power of the instrument, we shall not be able to detect the change, but, if greater, we shall be well aware of it. It appears, then, that the time-resolving power will be the interval required for the image on the photographic film to move its own width. Thus the time-resolving power depends both on the speed of the rotating mirror and on the width of the spectrum in the focal plane.

In order to limit the width of the spectrum, a horizontal slit was used, as well as the slit proper. Since the concave grating is not used in parallel light, the system is astigmatic. The conjugate focus of a line in the focal plane perpendicular to the spectral lines is farther from the grating than the conjugate focus of the lines themselves. The spectrograph slit is of course at the conjugate

focus of the spectral lines, but the horizontal slit must be placed at the conjugate focus of the line in the focal plane perpendicular to the spectral lines. The width of the second slit is governed by the intensity of the light-source. In the present work, the width used was such that the spectrum was 0.5 mm wide in the focal plane.

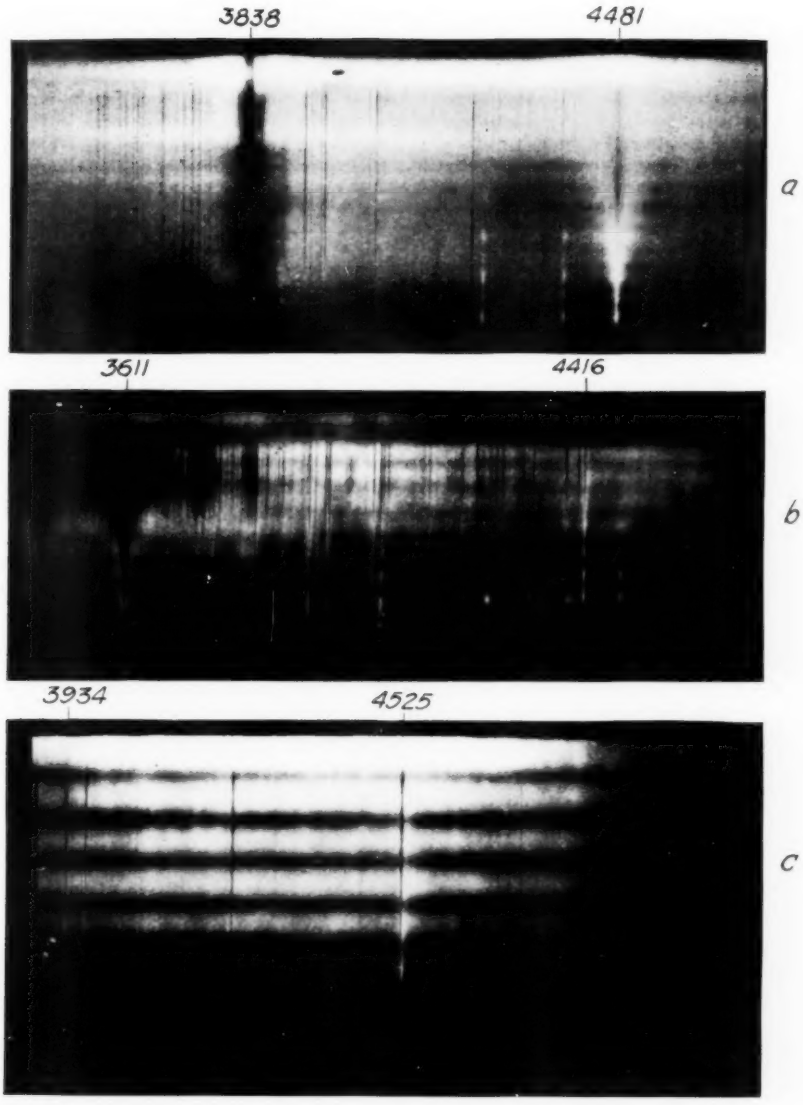
In most of the work to be described, the speed of the mirror was about 150 rev. per sec., corresponding to a motion of the spectrum along the film at the rate of about 450 m per sec. Assuming that uncertainties of measurement along the axis of the film arising from the finite width of the spectrum and a possible lack of critical focus do not exceed 0.5 mm, we find the time-resolving power to be of the order of one one-millionth of a second.

The condensers.—The spectra studied were produced in the manner described by Anderson. Two different condensers were used. One of them, which has already been described by Anderson,[1] consists of 200 single-strength window-glass plates, 20×24 inches, having tin-foil coatings 17×21 inches. Its capacity is about 1 microfarad, and in use was charged to 20,000 volts. The second condenser was also built under Anderson's direction. The plates, furnished by the Mississippi Glass Company, are 36×36 inches and $\frac{7}{16}$ inch thick. A closely woven wire gauze 32×32 inches was imbedded in the center of the plates during the manufacture, and a single wire was brought out on one side to serve as a lead. The plates are stacked in holders with the leads of alternate plates on opposite sides. All the leads on the same side are joined to a common terminal. This type of condenser can be charged to a much higher voltage than the ordinary form, and in the present work a voltage of 55,000 was used. During the assembly, the condenser plates were tested in pairs at 85,000 volts, but on account of surge difficulties it was not thought safe to use the whole condenser at this voltage. The complete condenser consists of 150 plates, which give a capacity of 0.6 microfarad.

As the intensity of the light varies with the oscillations present in the explosions, the oscillations themselves furnished a time scale very convenient for practical purposes. After having once determined the period of each of the electrical circuits, time differences

[1] *Mt. Wilson Contr.*, No. 269; *Astrophysical Journal*, **59**, 76, 1924.

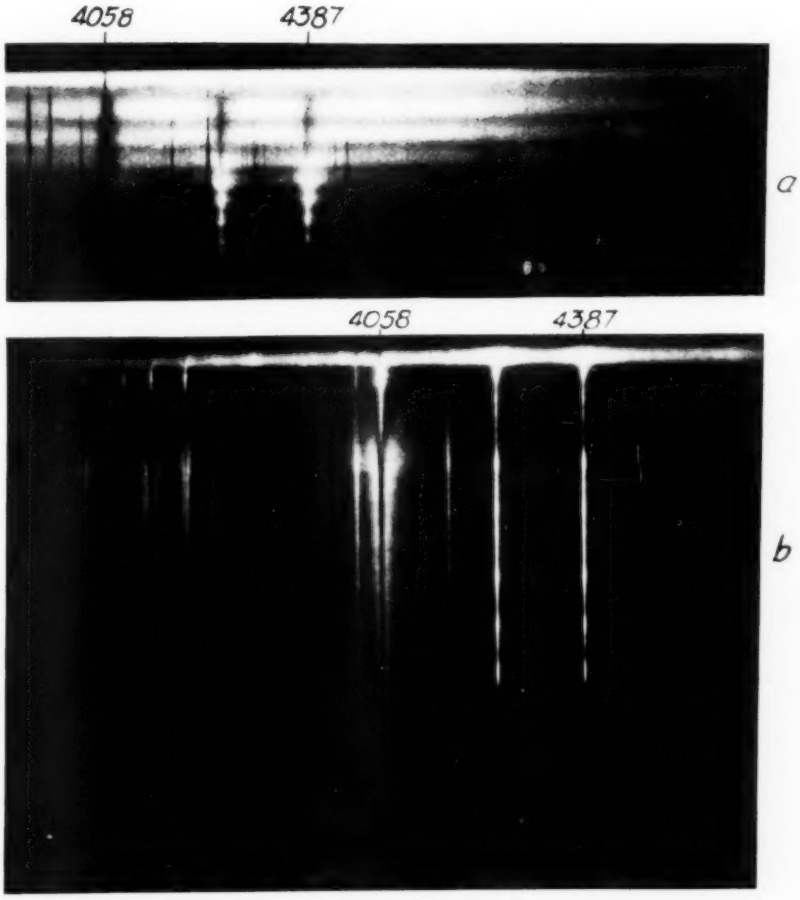
PLATE VIII



SPECTROGRAMS WITH ROTATING-MIRROR SPECTROGRAPH

a, Magnesium, 55,000-volt condenser. Note reversal of λ 4481
b, Cadmium, 55,000-volt condenser
c, Tin, 20,000-volt condenser

PLATE IX



SPECTROGRAMS OF LEAD WITH ROTATING-MIRROR SPECTROGRAPH

a, 55,000-volt condenser; *b*, 20,000-volt condenser

on the spectrograms were determined by comparison with the separation of the oscillations. The frequency of the 20,000-volt circuit was 87,000, and that of the 55,000-volt circuit, owing to much less inductance, was 185,000. This makes the maximum current in the 20,000-volt circuit about 10,700 amperes, and in the 55,000-volt circuit, about 40,000 amperes.

Some of the explosions studied were produced in air, while others were confined within a slotted block of wood. These blocks were of oak, $2 \times 2 \times 2\frac{1}{2}$ inches, with a $\frac{1}{8}$-inch slot, $\frac{3}{4}$ inch deep, cut the long way in each block. Holes were drilled in the sides and electrodes, 2 inches apart, inserted in such a manner that their tops were just above the bottom of the slot.

DISCUSSION OF SPECTROGRAMS

The spectra of a number of elements were examined in the region from λ 3000 to λ 5000. Very great differences were found in the behavior of different lines. The details for *Pb*, *Sn*, *Al*, *Cu*, *Cd*, and *Mg* are shown in the tables. In general, the arc lines were found to be completely reversed, while the spark lines frequently appeared in emission. The latter were generally strongest at the peaks of the oscillations, and some of them appeared only on the peaks. Ordinarily these lines disappeared when the oscillations ceased; but, as may be seen from the reproductions, there were large variations in behavior.

The lines were also found to behave differently with the two condensers. For example, when the explosions were produced with the 20,000-volt condenser, the two spark lines of *Pb*, λ 4245 and λ 4387, appeared as sharp lines and showed no tendency to reverse. With the 55,000-volt condenser, they became very broad and diffuse and showed definite reversal (see Plate IX). As a rule, the spectra obtained with the second condenser were almost wholly absorption spectra.

The spectra also behaved differently when the explosions were confined in a slot and when produced in the open air. The difference was very marked when the 20,000-volt condenser was used, but less noticeable in the case of the 55,000-volt condenser. With the lower-voltage condenser, confining the explosions increased

the strength of the continuous spectrum and also the tendency for lines to reverse. When the higher-voltage condenser was used, the difference was not so marked, for in this case the continuous spectrum was already quite strong in the unconfined explosions, and confining them added little to its strength.

The presence of the continuous spectrum is interesting in itself. In the case of most of the elements studied it is fairly strong throughout the third half-oscillation, and in some cases it persists as late as the fifth. Direct rotating-mirror photographs of the explosions show that by the time the third half-oscillation occurs, the vapor is expanding relatively slowly, from which it may be inferred that the pressure is not much above 1 atmosphere. This is significant in that it shows that we have a mass of vapor, certainly not much above atmospheric pressure, in which the excitation is sufficiently high to produce radiation almost entirely continuous. Just how much of this excitation is electrical, and how much is due to temperature, is of course not known. But the strongly marked increase in the continuous spectrum with the development of the electrical oscillations does not necessarily preclude a pure temperature excitation, since the effect of the current during the peaks of the oscillations may be only to increase the temperature of the vapor.

The fact that the enhanced lines appear most prominently when the continuous spectrum is strongest lends weight to the hypothesis that the quanta contributing to continuous radiation are produced when ionized atoms recombine. When recombination occurs, we should expect the sum total of the change in potential energy of the system, plus the kinetic energy of the electron relative to the atom, to be radiated in a single quantum. But no two of these quanta need have anything like the same value. The kinetic energy of the electron may have almost any value, and in recombining the electron may stop in any one of many orbits, so that the potential energy contributed to the quantum radiated can have a wide range of values. However true or false this picture may be, it is at least in qualitative agreement with the foregoing, and, furthermore, it explains the existence of the continuous background found in spark spectra.

Another interesting feature is the behavior of impurity lines. In general, for the first six or eight millionths of a second, the spectrum is that of the element under observation, and practically no impurity lines appear. Those that do appear, air lines in the case of unconfined explosions and calcium lines when the explosions are confined, apparently arise from neighboring materials rather than from the material under observation. The source of the air lines is obvious, while the calcium lines probably originate in the wooden blocks. This effect is noticeable in the reproduction of the cadmium spectrogram.

In one of the aluminum spectrograms the following impurity lines were identified in the region λ 3510–λ 4500:

Lead:	λ 3572.95	λ 3842.2
	3639.72	3854.11
	3683.62	4058.00
	3740.20	4245.42
	3835.15	4387.11

No trace of λ 4019.20 or λ 4168.19

Calcium:	λ 3933.81	λ 4226.90
	3968.62	4307.90

Iron:	λ 3553.87	λ 3720.09	λ 3786.81	λ 3878.19	λ 4202.20
	3557.02 (D ?)	3727.79	3795.12	4045.99	4260.68
	3565.54	3735.02	3816.00	4063.77	4271.95
	3570.29	3737.30	3820.61	4071.92	4325.97
	3581.38	3745.70	3826.07	4118.70	4383.71
	3585.88 (D ?)	3749.62	3828.00	4132.25	4404.95
	3618.91	3758.39	3834.40	4143.59	
	3621.61	3763.99	3840.61	4144.08	
	3631.60	3765.69	3860.03	4181.94	
	3648.00	3767.35	3872.70	4199.25	

EXPLANATION OF TABLES

For convenience the lines were classified as follows:

I. Pure absorption lines which remain sharp throughout their existence.

II. Pure absorption lines which are somewhat diffuse.

III. Pure absorption lines which widen very greatly during certain phases of the explosions.

IV. Strongly reversed lines showing emission edges and only a slight tendency to vary with the oscillations.

V. Diffuse lines showing faint reversal and pronounced variation with the oscillations.

VI. Diffuse lines showing no trace of reversal but pronounced variation with the oscillations.

VII. Sharp lines showing no trace of reversal, but definite variation with oscillations.

VIII. Diffuse lines showing no trace of reversal and appearing only on the peaks of the oscillations.

IX. Sharp lines showing no trace of reversal and appearing only on the peaks of the oscillations.

This classification is purely arbitrary, and in many cases not sufficient, but a detailed discussion of the behavior of each line is out of the question. Intensities are given merely as *w*, *m*, or *s*, meaning weak, medium, or strong. A more elaborate system seems unnecessary. In a few cases, the series classification is given after the wave-length. In the column headed "Remarks" is listed the time of first appearance in terms of the half-oscillations. For example, "late in 3rd" means that the line first appeared on the spectrogram during the latter part of the third half-oscillation. Any extraordinary behavior of the line is also noted in that column.

TABLE I

TIN

50,000-Volt Condenser, Explosions Confined in Block

Wave-Length	Int.	Class	Remarks
4525.....	*s*	I	Appears at beginning
	Impurities		
3934 *Ca*.....	*m*	I	Appears in 2nd
3969 *Ca*.....	*m*	I	Appears in 2nd
4227 *Ca*.....	*m*	I	Appears in 2nd
4737 *C*.....	*w*	Band	Four heads show faintly in 4th, 5th, and 6th

TABLE II

MAGNESIUM

50,000 Volt Condenser, Explosions Unconfined

Wave-Length	Int.	Class	Remarks
3829.....	*s*	III	Appears at beginning
3832.....	*s*	III	Appears at beginning
3838.....	*s*	III	Appears at beginning
4481.....	*s*	V	Appears at beginning; very wide at first (possibly 50 A)

TABLE III

CADMIUM

Wave-Length	55,000-Volt Condenser, Explosions Confined in Block			20,000-Volt Condenser, Explosions Unconfined		
	Int.	Class	Remarks	Int.	Class	Remarks
3081 $1p-2s$...	*m*	II	Begins late in 1st	.....	.....	
3081 $1p-2s$...	*m*	II	Begins late in 1st	.....	.....	
3253 $1p-2s$...	*m*	II	Begins late in 1st	.....	.....	
3261 $1S-1p_2$...	*m*	I	Appears at beginning; very sharp throughout	.....	.....	
3404 $1p-2d$...	*s*	III	Appears at beginning	*s*	IV	Appears at beginning
3466 $1p-2d$...	*s*	III	Appears at beginning	*s*	IV	Appears at beginning
3536.....	.....	.....	Not present	*m*	IX	Appears at 1st and 2nd only
3611 $1p-2d$...	*s*	III	Appears at beginning	*s*	IV	Appears at beginning
4416.....	*s*	V	Appears late in 1st	*m*	VII	Very strong in 1st
4678 $1p-1s$...	*s*	II	Appears late in 1st	.....	.....	
4800 $1p-1s$...	*s*	II	Appears late in 1st	.....	.....	
5086 $1p-1s$...	*s*	II	Appears late in 1st	.....	.....	
	Impurities					
3159 *Ca*.....	*w*	I	Begins late in 2nd	.....	.....	
3179 *Ca*.....	*w*	I	Begins late in 2nd	.....	.....	
3934 *Ca*.....	*m*	I	Begins late in 1st	*m*	VII	Begins late in 1st
3969 *Ca*.....	*m*	I	Begins late in 1st	*m*	VII	Begins late in 1st
4227 *Ca*.....	*m*	I	Begins late in 1st	*m*	VII	Begins late in 1st

A NEW ABSORPTION PHENOMENON

In the case of a number of explosion spectrograms of *Al*, *Pb*, *Cd*, *Ca*, and *Mg*, a new absorption phenomenon presented itself. For a very short interval, usually not more than about three-millionths of a second, that part of the explosion which was projected on the

TABLE IV

ALUMINUM

Wave-Length	55,000-Volt Condenser, Explosions Unconfined*			20,000-Volt Condenser, Explosions Unconfined		
	Int.	Class	Remarks	Int.	Class	Remarks
3587.....	*s*	V	Very wide in first gradually narrowing to a class IX line in the 5th or 6th	*s*	VI	In some cases this line appears in the 1st as a broad diffuse line and continues until about the 4th when it disappears. In other cases it appears very faintly in the 1st and then disappears until the 3rd when it appears quite strong and persists until the 8th or 10th
3602.....	*m*	IX	Appears on peaks of 2nd, 3rd, and 4th	.....	.....	
3613.....	*m*	IX	Appears on peaks of 2nd, 3rd, and 4th	.....	.....	
3944.....	*s*	I	Appears at beginning	*s*	IV	These lines appear throughout and show a marked widening about the time 3587 disappears
3962.....	*s*	I	Appears at beginning	*s*	IV	
4480.....	*w*	VII	Appears on peaks of 2nd to 5th	.....	.....	
4513.....	*m*	IX	Appears on peaks of 2nd to 5th	.....	.....	
4530.....	*m*	IX	Appears on peaks of 2nd to 5th	.....	.....	
4664.....	*s*	VI	Appears first in 3rd	*s*	VI	Behaves like 3587
	Impurities					
3995 *N*.....	*m*	IX	Appears on peaks of 1st, 2nd, 3rd, and 4th	*w*	IX	Appears in 1st only
4447 *N*.....	*m*	IX	Appears on peaks of 1st, 2nd, 3rd, and 4th	.....	.....	
4631 *N*.....	*m*	IX	Appears on peaks of 1st, 2nd, 3rd, and 4th	.....	.....	

* Explosions confined in block:

The *N* lines do not appear and *Ca* lines come up in the usual manner.

The two strong lines λλ 3944 and 3961 develop very wide wings in the beginning; the central portion, however, remains quite sharp.

The spark lines λλ 4480, 4513, and 4529 disappear almost entirely, showing only as mere traces on a few spectrograms.

λ 4664 appears later than before, beginning with the 5th. It is rather diffuse and shows more pronounced variation with the oscillations.

The *Al* band λ 4842.40 shows faintly in the 1st.

slit of the spectrograph became highly absorbing and produced no photographic effect. As may be seen from the reproductions, the light appears to be completely cut off. In the regions very close to strong arc lines this cutting off occurs a little later than in more remote regions, so that the general appearance is that of an infin-

TABLE V

LEAD

Wave-Length	55,000-Volt Condenser, Explosions Confined in Block			20,000-Volt Condenser, Explosions Unconfined		
	Int.	Class	Remarks	Int.	Class	Remarks
3574	*s*	III	Begins in 2nd, widens during 3rd	*s*	V	
3640	*s*	III	Begins in 2nd, widens during 3rd	*s*	V	These lines become class IV lines after the 3rd
3672	*s*	II	Begins in third	*s*	V	
3684	*s*	III	Begins in 2nd, widens during 3rd	*s*	V	
3740	*s*	III	Begins in 2nd, widens during 3rd	*s*	V	
3786	.....	.....	No trace	*m*	VII	Appears late in 1st
3854	.....	.....	No trace	*m*	IX	Appears at very beginning of 1st again in 3rd to 8th
3833	.....	.....	No trace	*w*	IX	On peaks of 3rd to 8th
3842	.....	.....	No trace	*w*	IX	On peaks of 3rd to 8th
4020	*m*	I	Begins in 2nd	.....	VII	Begins at end of 1st. Trace of reversal on some exposures
4058	*s*	II	Appears throughout	*s*	V	Changes to class IV after the 3rd
4168	*w*	I	Begins in 2nd	.....	VII	Behaves like 4019.76
4245	*s*	V	Almost entirely reversed in 1st	*s*	VII	Diffuse in 1st
4387	*s*	V	Almost entirely reversed in 1st	*s*	VII	Diffuse in 1st
4437	*m*	I	Begins in 3rd	.....	.....	
4455	*m*	I	Begins in 3rd	.....	.....	
5006	*m*	I	Begins late in 1st	.....	.....	
	Impurities					
3248 *Cu*	*w*	I	Begins in 3rd	.....	.....	
3274 *Cu*	*w*	I	Begins in 3rd	.....	.....	
3934 *Ca*	*m*	I	Begins late in 1st	*m*	VII	Begins late in 1st
3944 *Al*	*w*	I	Begins in 3rd	*w*	VII	Begins in 3rd
3962 *Al*	*w*	I	Begins in 3rd	*w*	VII	Begins in 3rd
3969 *Ca*	*m*	I	Begins late in 1st	*m*	VII	Begins late in 1st
4227 *Ca*	*m*	I	Begins in 2nd	*w*	VII	Begins in 3rd
4283 *Ca*	*w*	I	Begins in 3rd	.....	.....	
4289 *Ca*	*w*	I	Begins in 3rd	.....	.....	
4299 *Ca*	*w*	I	Begins in 3rd	.....	.....	
4303 *Ca*	*w*	I	Begins in 3rd	.....	.....	
4308 *Ca*	*w*	I	Begins in 3rd	.....	.....	
4319 *Ca*	*w*	I	Begins in 3rd	.....	.....	

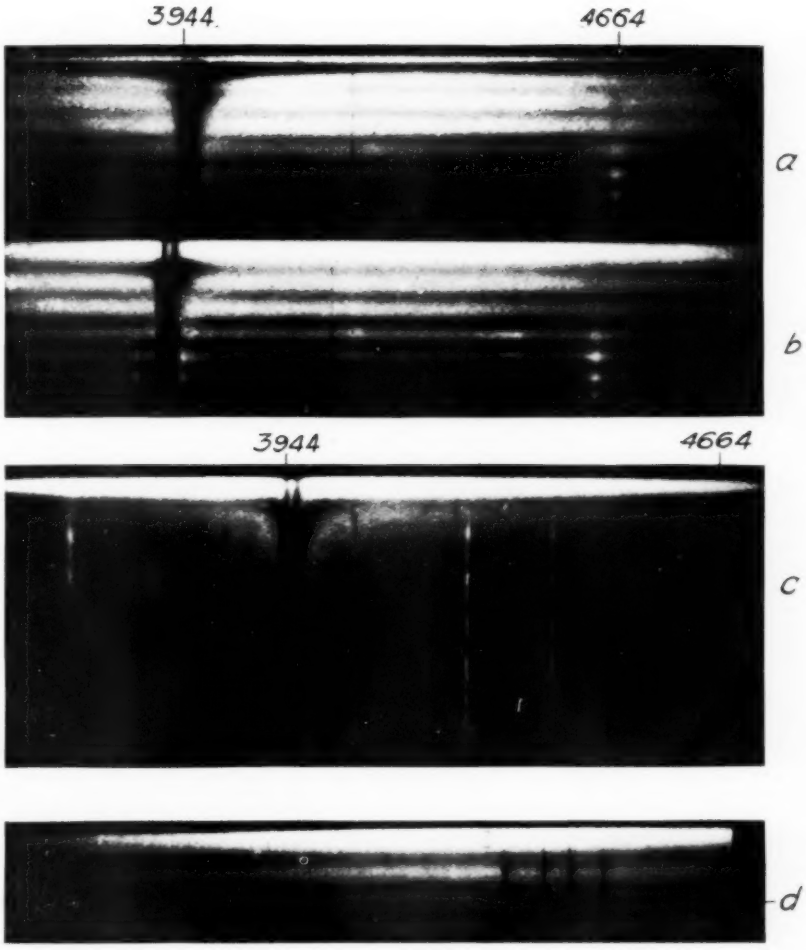
itely wide absorption line rapidly becoming narrow. This delayed absorption is best illustrated by the aluminum spectrogram (Plate X), in which the light from the explosion first appears to be

TABLE VI

COPPER

Wave-Length	55,000-Volt Condenser, Explosions Confined in Block			20,000-Volt Condenser, Explosions Unconfined		
	Int.	Class	Remarks	Int.	Class	Remarks
2824	w	II	Appears at beginning	.....	.....	
2863	w	II	Appears at beginning	.....	.....	
2951	m	I	Appears at beginning	.....	.....	
2998	w	I	Appears at beginning	.....	.....	
3011	m	I	Appears at beginning	.....	.....	
3036	m	I	Appears at beginning	.....	.....	
3064	m	I	Appears at beginning	.....	.....	
3094	m	II	Begins late in 1st	.....	.....	
3100	m	II	Begins late in 1st	.....	.....	
3109	m	II	Begins late in 1st	.....	.....	
3126	m	II	Begins late in 1st	.....	.....	
3143	m	II	Begins late in 1st	.....	.....	
3194	w	I	Appears at beginning	.....	.....	
3208	w	I	Appears at beginning	.....	.....	
3248	s	III	Very wide throughout	.....	.....	
3274	s	III	Very wide throughout	.....	.....	
3291	m	I	Appears at beginning, slightly diffuse	.....	.....	
3308	m	I	Appears at beginning, slightly diffuse	.....	.....	
3317	w	II	Appears at beginning, slightly diffuse	.....	.....	
3338	w	I	Appears at beginning, very sharp	.....	.....	
3355	w	I	Begins in 2nd	.....	.....	
3450	w	I	Begins late in 1st	.....	.....	
3476	w	I	Begins late in 1st	.....	.....	
3484	w	I	Begins late in 1st	.....	.....	
3512	w	I	Begins late in 1st	.....	.....	
3599	m	I	Appears at beginning	.....	.....	
3602	m	I	Appears at beginning	.....	.....	
4023	.....	.....	A mere trace appearing in the 5th and 6th only	s	VI	Appears throughout; no variation with oscil's
4063	.....	.....	A mere trace appearing in the 5th and 5th only	s	VI	Appears throughout; no variation with oscil's
4076	.....	.....	.....	w	VII	Appears throughout; no variation with oscil's
4081	.....	.....	.....	w	VII	Appears throughout; no variation with oscil's
4104	.....	.....	.....	w	VII	Appears throughout; no variation with oscil's
4123	.....	.....	.....	m	VII	Appears throughout; no variation with oscil's
4178	.....	.....	.....	m	VII	Appears throughout; no variation with oscil's
4249	.....	.....	.....	m	VII	Appears throughout; no variation with oscil's
4259	.....	.....	.....	m	VII	Appears throughout; no variation with oscil's

PLATE X



SPECTROGRAMS WITH ROTATING-MIRROR SPECTROGRAPH

a, *b*, *c*, Aluminum, showing behavior of absorption band near two strong arc lines
d, Lead, showing an absorption band on the peak of the third half-oscillation

TABLE VI—*Continued*

Wave-Length	55,000 Volt Condenser, Explosions Confined in Block			20,000 Volt Condenser, Explosions Unconfined		
	Int.	Class	Remarks	Int.	Class	Remarks
4275	*m*	IV	Appears at beginning	*s*	VII	Appears throughout; no variation with oscil's
4378	*m*	IV	Appears at beginning	*s*	VII	Appears throughout; no variation with oscil's
4416	*m*	IV	Appears at beginning	*w*	VII	Appears throughout; no variation with oscil's
4510	*m*	IV	Appears at beginning	*m*	VII	Appears throughout; no variation with oscil's
4540	*m*	IV	Appears at beginning	*m*	VII	Appears throughout; no variation with oscil's
4587	*m*	IV	Appears at beginning	*m*	VII	Appears throughout; no variation with oscil's
4651	*m*	IV	Appears at beginning	*m*	VII	Appears throughout; no variation with oscil's
4675	*w*	IV	Appears at beginning	.....	.....	
4705	*w*	IV	Appears at beginning	.....	.....	

completely cut off, except in the region within a few angstroms from the two strong arc lines λ 3944 and λ 3961. Then as time progresses, the vapor becomes transparent to wave-lengths remote from these two lines, but opaque to wave-lengths within a few angstroms from them. Immediately after the absorption sets in, the appearance is of an infinitely wide absorption line having an emission center some 50 A wide, with the emission core itself showing two sharp absorption lines upon its central region. In the lead spectrogram (Plate IX*b*) the same effect is seen, except that in this case the lack of a continuous background makes it less prominent. Here the arc lines λλ 3574, 3640, 3684, 3740, and the very strong arc line λ 4058, play the prominent part. The phenomenon shows considerable variation, both as regards duration, as can be seen from the series of aluminum spectrograms, and as to time of occurrence. In one of the lead explosions, it occurred about twenty-five millionths of a second after the beginning of the explosion. Ordinarily it coincides with a minimum of one of the oscillations, but not always. Thus on the lead spectrogram (Plate X*d*), one of these "absorption bands" was found on the peak of the third half-oscillation. This particular one was of very short duration, somewhat less than two millionths of a second.

It is very probable that this absorption occurs only over a very small area of the explosion. Direct rotating-mirror photographs show that the explosions of elements which exhibit the effect

have a mottled appearance. Small areas apparently give off no light, or at least not enough to affect the photographic film. The area of these spots is only a few square millimeters, and it seems very probable that they are the regions in which the absorption described above is occurring. It would be very strange, indeed, if the whole mass of vapor stopped emitting light for a short time, and if this ever occurs the direct rotating-mirror photographs should show it; but no such effect was found, and it seems reasonable to conclude that the absorption occurs only in small areas at any one time.

No explanation of the phenomenon is offered. Possibly it may be a type of photo-electric absorption; but while this might explain the general absorption, it is difficult on this basis to see why the absorption should be delayed in the vicinity of strong arc lines. The fact that it seems to occur only in small regions at any instant might be explained as follows: Suppose that for some reason a large percentage of the atoms in some small region are in the same state of excitation, such that they can be ionized by the absorption of a quantum of visible light. We might then expect the vapor in this small region to be opaque to all wave-lengths below that having just the ionizing energy; in other words, to all wave-lengths below some long wave-length limit. In the case of aluminum, such a limit was looked for. By using a wide slit and red sensitized films, the spectrum was photographed out to λ 7500, but no long wave-length limit was found. This, of course, has very little bearing on the explanation, for even though the absorption were of a photo-electric nature, it might be produced by a mixture of atoms in various states of excitation. In this case the atoms in different states would have different long wave-lengths as limits, and we should not expect any very definite red limit to the absorption. But even if we grant that photo-electric absorption may play a part, the delayed action in the neighborhood of strong arc lines remains to be explained. To the writer at least, photo-electric absorption is therefore very unsatisfactory as an explanation of the phenomenon.

Dr. Anderson has suggested that anomalous dispersion may furnish the real explanation. In case the surface of the incandescent mass takes the proper shape, the vapor may behave very

much as described by Julius.[1] The fact that the phenomenon is associated with strong absorption lines is very much in line with this suggestion, but further work will be necessary before the question can be settled.

THE RESISTANCE OF METALLIC VAPORS

During the study of the explosions, it developed that some metals were more difficult to explode than others. Anderson[2] has reported that when wires of copper, silver, or gold were exploded, a spark would pass across the space between the leads to the electrodes which supported the wires, unless they were well separated, a part of the discharge thus being shunted around the explosion. It was found, however, that by keeping the leads well separated, all the discharge could be made to go through the explosion.

In order to investigate this phenomenon, a sphere gap was placed in parallel with the wire to be exploded, so that maximum voltage built up across the vapors of the explosion could be measured. The electrodes supporting the wires were arranged so that their separation could be varied, and measurements were made with separations of from 1 to 10 cm. The observations consisted in determining the minimum separation of the sphere gap which would force all the discharge through the vapors of the explosion. The 55,000-volt condenser was used.

Curves showing the electrode separation, i.e., the length of wire exploded, against the voltage built up across the vapors of the explosion, were plotted for a number of elements. A few of these curves are shown in Figure 4. They appear to depart only slightly from straight lines through the origin. As a basis for comparison, the minimum voltage in kilo-volts corresponding to a 5-cm length of wire is listed for all the elements studied:

Cu 79 k.v.	*Au* 75–85	*W* 58	*Al* 51	*Li* 42
Ag 81	*Ni* 72	*Zn* 58	*Pb* 49	*Fe* 39
			Sn 51	

As the supply of gold wire gave out before sufficient data were obtained, a definite value for this element cannot be given. The

[1] *Astrophysical Journal*, **12**, 185, 1900.

[2] *Mt. Wilson Comm.*, No. 82; *Proceedings of the National Academy of Sciences*, **8**, 231, 1922.

evidence on hand indicates, however, that its value is very close to those of copper and silver.

The fact that these three "high" elements belong to the same group in the periodic system suggests that elements in any one group

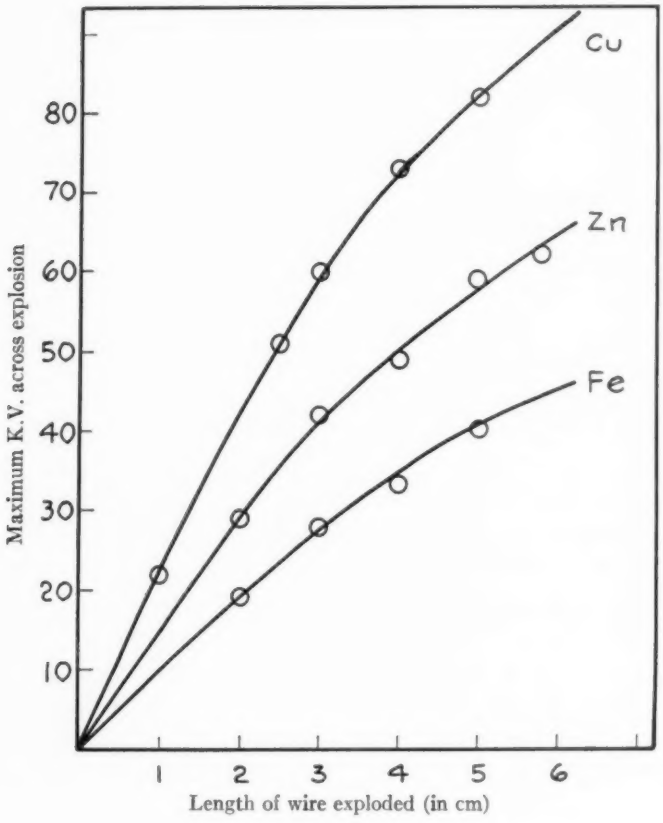


FIG. 4

should behave alike in the explosions, but a glance at the results for the elements just listed shows that the agreement is rather haphazard.

Two 1.5-inch spheres were used for the gap, and the voltages listed on the curves were computed in the usual way. That some of the voltages are much higher than that used on the condenser

is not surprising when one remembers that we are dealing with rapidly changing currents.

In order to determine just when the voltage across the explosion reached a maximum, the apparatus was so arranged that light from both the gap and the explosion fell on the slit of the rotating-mirror spectrograph. As far as could be determined by means of the spectrograph, the beginning of the spark and the beginning of the explosion seemed to be simultaneous. Probably the wire first vaporized and then developed a high resistance, but did not become sufficiently luminous to photograph until the high-resistance stage was reached.

When the sphere gap was set near the critical position for the wire in question, only part of the current of the first half-oscillation passed through the gap. The balance and that of all subsequent oscillations passed through the vapors of the explosion. If the gap was made sufficiently short, practically all the discharge could be made to pass across the gap.

The mass of the wire exploded seems to have very little effect on the determinations of voltage as wires of various sizes of the same metal gave similar sphere-gap settings. Screening the gap from the light of the explosion made no noticeable difference. It is thought that the measured voltages are proportional to the resistance of the various metallic vapors.

In conclusion, the author wishes to express his deepest appreciation to Dr. J. A. Anderson, under whose direction this work was done.

MOUNT WILSON OBSERVATORY
September 1924

REVIEWS

Probleme der Astronomie. Festschrift für Hugo v. Seeliger dem Forscher und Lehrer zum Fünfundsiebzigsten Geburtstage. Berlin: Julius Springer, 1924. Portrait, 3 plates, 58 illustrations and diagrams. Pp. 475. 45 gold marks, bound.

In this noteworthy volume of essays thirty-six disciples have proffered to their master a birthday homage that death has all too soon transformed into a more definitive memorial. Seeliger passed away soon after the appearance of this volume but not too soon for its spirit, and perhaps its text, to have brought some thrill of gratification at its timely recognition of his influence, as investigator and teacher, upon the development of twentieth-century astronomy. The thirty-six authors of these essays themselves constitute an impressive group of leaders in that development and most of them still remain in active life. Two, Schwarzschild and Schnauder, have preceded their teacher into the final bourne, and their essays are posthumously published. Certain of the others are designated as reprinted matter but for most of them no indication of this kind is given.

Quite naturally the essays are of very diverse character and quality. Their sole apparent bond of union is the leader in whose honor they are collected, and they present a diversity of subject and treatment that quite precludes any useful classification of their content. They range from cosmogony and philosophy through celestial mechanics and stellar statistics to the technical details of current research in astrometry and astrophysics. Some trace of Seeliger's personal characteristics and influence may be found in their prevailingly mathematical mode of thought and expression, and his own research work furnishes a basis for several of the papers. Nevertheless, their diversity of character and subject matter is such that few astronomers will be able to pass critical judgment upon all of them. A larger number of readers may dissent, probably will dissent, from some of the views expressed and advocated, but a still greater number of students of the heavens may find instruction and profit through a perusal of the volume.

The title, *Problems of Astronomy*, is well chosen since collectively the essays furnish a conspectus of recent astronomical research which while

not professing to be complete or exhaustive is yet fairly typical of modern work and progress. The reviewer confesses to a certain feeling of surprise that the pupils of a single teacher should constitute so large a factor in that progress. Considered geographically and linguistically, about two-thirds of the essays appear in the German language and are obviously from German and closely related sources. English is represented by a half-dozen papers and French by a single title, coming from a Slavic source. Scandinavian and Dutch sources are represented by contributions about equal in number to those coming from England and America, but the Latin world contributes not a title to the list. One wonders whether Seeliger's influence was limited by an ethnic boundary or whether merely the content of the present volume has been restricted by postbellum antipathies.

Taken as a whole, the volume possesses decided interest in subject matter and value as a résumé of recent progress in astronomy. It should find a cordial welcome among astronomers.

GEORGE C. COMSTOCK

Astronomie. Edited by J. HARTMANN. Leipzig and Berlin: B. G. Teubner, 1921. Pp. x+640; figs. 40; pls. 8. Price, about $5.00.

This volume forms one of the series entitled "Die Kultur der Gegenwart," which also includes volumes on mathematics, the nature sciences, and medicine. The volume on physics appeared in 1915, under the editorship of E. Warburg, with contributions from many well-known physicists.

Astronomie is divided into sections written by different authors, as follows:

"Die Entwicklung des astronomischen Weltbildes im Zusammenhang mit Religion und Philosophie," by Franz Boll, 56 pages. "Die Zeitrechnung," by F. K. Ginzel, 35 pages. "Die Zeitmessung," by J. Hartmann, 46 pages. "Astronomische Ortsbestimmung," by Leopold Ambronn, 39 pages. "Erweiterung des Raumbegriffes," by A. von Flotow, 39 pages. "Mechanische Theorie des Planetensystems," by J. von Hepperger, 45 pages. "Physische Erforschung des Planetensystems," by K. Graff, 57 pages. "Physik der Sonne," by E. Pringsheim, 55 pages. "Physik der Fixsterne," by P. Guthnick, 138 pages. "Das Sternsystem," by H. Kobold, 55 pages. "Die Beziehungen der Astronomie zu Kunst und Technik," by L. Ambronn, 32 pages. "Die Gravitation," by S. Oppenheim, 33 pages.

The method of presentation adopted in a work like this obviously brings a great deal of variety, and the reader will give special attention

to the different sections according to his own tastes. The style naturally differs with the author and subject. I shall have to confess that we found the first section rather dull, while that entitled "Physics of the Fixed Stars," by Guthnick, was very interesting and thoroughly up to date. This is the longest section, and is probably the one that will appeal to the largest number of readers. Guthnick's divisions are four in number, covering the conception of a fixed star, methods of research, results of research, and physical theories of the stars. The third naturally occupies the greatest space, nearly one hundred pages. The author discusses the following topics: photometry, colorimetry, spectroscopy, the modern view of the spectral series, the effective temperature of the stars, spectroscopic determination of absolute magnitudes, spectral and visual binaries, variable stars, star clusters and nebulae. The references are numbered and are collected in a bibliography of about four pages at the end of this division, as is the practice throughout the work. This part, as we are told in the preface, was rewritten only a few months before the appearance of the book in 1921, and it adds a touch of freshness which does not so much characterize some of the other chapters, written before the war.

Professor K. Graff's chapter on the physical investigations of the planetary systems is written in a thoroughly logical and reasonable manner, and deals with some matters in dispute in a conservative, but judicial, way.

Professor E. Pringsheim's chapter on the physics of the sun was written before the war and does not bring us much beyond his own work upon the subject, which appeared a few years earlier.

The general tendency of the work is philosophical rather than purely didactic. The accomplished editor did not choose for himself those topics which might be regarded as the most interesting for treatment, but he has done his work both as an author and as editor of the whole in a careful way. The volume will have a special place among the treatises upon astronomy and will be frequently consulted by those having it.

The illustrations of the book are not noteworthy and suffer somewhat from the effects of the war. Aside from the diagrams throughout the text, they are gathered in eight plates at the end of the volume.

We hope that there will be a demand for a second edition of this work, so that the different parts can be made more nearly simultaneous in the view they give of some phases of the subject.

We congratulate both the editor and his publishers on their courage in completing this volume under the difficult conditions which intervened between its inception and its completion.

E. B. F.

Observations of the Total Solar Eclipse of January 24, 1925, Made by Electric Companies Affiliated with the Consolidated Gas Company of New York. New York: Consolidated Gas Company, 1925. Pp. 42; 14 half-tones; figs. 17.

This handsome quarto pamphlet furnishes a fine illustration of the co-operation which public-service corporations can give to science in the study of natural phenomena.

Reports are given from various departments of the companies concerned, covering the photography of the eclipse and of its effects upon the illumination of the city, the photometry of the light of the sun during the partial and total phases, the determination of the exact limit of the shadow by men stationed on housetops, chiefly along Riverside Drive, and the record of the load on the electric and gas companies at the various stages of the eclipse.

The position of the edge of the umbra was sharply defined as falling at Ninety-sixth Street, by direct observation of whether or not the eclipse was total.

Photographs were secured with cameras of various sizes, up to 36 inches focal length.

We congratulate these corporations upon the scientific interest and appreciation evidenced by their officers.

E. B. F.

The Natural History of Crystals. By A. E. H. TUTTON. London: Kegan Paul, Trench, Trubner & Co., 1924. Pp. xii+287; 166 illustrations, including 32 plates. $5.00.

The author has spent a lifetime in the study of crystals, and during that time he has made important improvements in the apparatus used in measuring their physical constants, and employed the new equipment with such patience and skill that he has made incomparably the most accurate measures ever accomplished; he has done this, not merely on one crystal, but on a long series of them, which he prepared especially for the purpose, consisting of sixty-two different members of two isomorphous groups. He is therefore a recognized authority on the precise properties of crystals. It is a happy circumstance that he is not only remarkably successful in such laborious research, but is also a writer of no mean ability.

Tutton's book on crystals is written for the general reader and therefore not at all in the style of a textbook. The author has a real enthusiasm for his subject, which is evident on every page and aids materially in mak-

ing the book interesting and readable. The studious reader will have little difficulty in following the ideas of the author in the first part of the book, which deals with the historical development of the science of crystallography and the present methods of studying and describing crystals. It will be found that crystallographers had elaborated in great detail a theory of the "molecular" structure of crystals which the X-ray studies of the last decade have shown to be remarkably accurate, and also that the author took a very creditable part in this work, as a result of careful deductions from his elaborate measurements of crystals. In the latter part of the book, which deals with the effects of crystals upon light, the average reader will find many beautiful illustrations, and good descriptions of the apparatus needed to obtain them, but must not expect to be able to understand very fully how the crystals produce such effects.

It is an unusual experience to find a new book on science whose very first sentence is open to challenge, and is even indirectly at variance with later statements of the author himself. Tutton opens his Introduction with the statement that "no definition of life has yet been advanced which will not apply to a crystal." In the same paragraph he states that living tissue loses the power of growth, while crystals never do so.

It seems to the reviewer misleading to hold that the atoms in diamond are "loosely packed" (p. 122), when, in fact, they are closer together than in any other known substance.

In America the term "natural history" as a synonym of "science" has quite gone out of fashion; therefore the title of Tutton's new book will probably seem a bit archaic to readers in this country.

A. N. WINCHELL

THE SOLAR PHYSICS COMMITTEE

The report of the Solar Physics Committee of the International Astronomical Union is now in preparation for the triennial meeting of the Union in Cambridge in July. It is requested that anyone interested in solar investigation send to the chairman suggestions or recommendations for the report or for consideration by the full Committee in Cambridge.

CHARLES E. ST. JOHN, *Chairman*

MOUNT WILSON OBSERVATORY
January 15, 1925